THESIS

THE REVISED DUAL TASK SCREEN: ANALYSIS OF DUAL TASK MOTOR AND COGNITIVE COSTS IN HEALTHY, YOUNG ADULT ATHLETES

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ABSTRACT

THE REVISED DUAL TASK SCREEN: ANALYSIS OF DUAL TASK MOTOR AND COGNITIVE COSTS IN HEALTHY, YOUNG ADULT ATHLETES

Premature return-to-play clearance can put an athlete with sports-related concussion (SRC) at risk for further injury, making proper diagnosis and management of SRC in athletes crucial. However, objective measures that are currently used in SRC management have limitations, including poor test-retest reliability, reliance on baseline testing, and insufficient difficulty for high-performing athletes. More complex tasks, including dual task measures (i.e. simultaneous motor and cognitive task performance) can detect subtle, residual deficits in athletes with SRC. While dual tasks have been shown to have potential benefit for SRC management, many dual task paradigms are limited by high cost, long administration times, and low portability. Thus, we developed the revised Dual Task Screen (DTS), a measure designed to be completed and scored in fewer than 10 minutes using only portable, low-cost instruments. The revised DTS is comprised of two subtasks: a Lower Extremity (LE) subtask and an Upper Extremity (UE) subtask. This study evaluates if the revised DTS was sensitive to dual task motor and cognitive costs (i.e. significantly poorer performance on dual trials compared to single trials) in 22 healthy, young adult athletes. We observed statistically significant dual task motor costs for the primary and secondary motor outcome measures on the LE subtask, as well as the outcome measure on the UE subtask. While the revised DTS elicited numerical dual task cognitive costs on the LE outcome measure and UE outcome measure, only the UE subtask elicited performance

differences that were statistically significant. The results from our study indicate that the revised DTS is a promising and clinically feasible measure for use in SRC management.

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CHAPTER 1: INTRODUCTION

1.1 Purpose

The primary purpose of this thesis is to evaluate the sensitivity of our measure, the Dual Task Screen (DTS), to dual task motor and cognitive costs in healthy, young adult, female athletes. A dual task cost is reduced motor or cognitive performance during a dual task (i.e. motor + cognitive) compared to performance during a single task (i.e. motor only). The DTS has been developed for prospective, future use in adolescent and young adult athletes with sports-related concussion (SRC). In addition to understanding potential dual task motor and cognitive costs, this project may examine the neural underpinnings of behavioral performance using functional near infrared spectroscopy (fNIRS) neuroimaging. This study builds upon a DTS pilot study that was published by Stephens et al. in 2018. In that pilot study, Stephens et al. (2018) evaluated the feasibility and sensitivity of the original DTS to dual task motor costs in healthy, adolescent, female athletes. My thesis now uses a revised DTS with an older cohort and assesses if the DTS can elicit dual task motor and cognitive costs. Further, the fNIRS data that we have collected during the DTS could help establish if there are dual task *neurological* costs – defined as differences in neural activation in specific regions of the brain during dual tasks compared to single tasks. However, due to COVID-19 pandemic-related delays in fNIRS data acquisition and the complexity of data analysis, we have not included fNIRS data in this thesis work.

1.2 Background and Statement of Problem

Sports-related concussion, or SRC, is a form of mild traumatic brain injury (mTBI) that can result in short-term and long-term functional impairments (e.g. Gupta et al., 2019). In the United States, it is estimated that 1.6 to 3.8 million SRCs occur annually, however this number may be underestimated as many SRCs are undiagnosed (e.g. Cheng et al., 2019). Notably, the incidence of concussion is highest in individuals aged 9 to 22 years old who participate in group athletics (Zuckerman et al., 2015). Additionally, research has shown that women are at a greater risk for sustaining SRC compared to men, despite overall TBI incidence being higher in males (e.g. Zuckerman et al., 2015, Nguyen et al., 2016). Further, athletes with a history of sustaining a SRC have an increased likelihood of suffering another SRC upon return to their sport (Guskiewicz et al., 2003).

SRC can affect an athlete's performance and participation in their sport, but it can also affect other occupational domains, including work, school, rest, and sleep (AOTA, 2020; Gupta et al., 2019). Proper diagnosis and management of SRC in athletes is crucial to ensure their health and safety for return-to-play. The rapid onset and spontaneous recovery of SRC symptoms can make it difficult for athletes, coaches, and practitioners to recognize a SRC, which can result in misdiagnosis or underdiagnosis of the concussion (Daneshvar et al., 2011). Additionally, the non-specific nature of SRC symptoms further challenges return-to-play decision-making; for example, an athlete may not report their headaches because they have frequent headaches from other causes (e.g. seasonal allergies) and may not recognize this as an SRC-induced symptom. This missed symptom could then lead to premature return-to-play if the athlete reports no known SRC-symptoms to their health care provider. Prevention of premature return-to-play following a SRC may decrease the likelihood of sustaining a subsequent SRC (Schatz et al., 2006). The current gold standard for return-to-play decision-making after a SRC uses self-reported symptoms, physical examination, and cognitive performance (Phillips & Woessner, 2015). Despite the existence of a gold standard, most SRC providers rely solely on symptom reports and do not incorporate other components of this standard (Haider et al., 2018).

Despite their advantages over symptom-reporting only, objective measures (e.g. balance and neurocognitive testing) that are currently used in SRC management have limitations, including poor test-retest reliability, reliance on baseline testing, and insufficient difficulty (Broglio et al., 2017; Broglio et al., 2018, Howell et al., 2019). To address some of these limitations, particularly related to measure difficulty, research has focused on developing dual tasks paradigms for athletes with SRC (Howell et al., 2017). Dual tasks paradigms require individuals to perform a motor task and distractor task (often a cognitive task), simultaneously. Subsequently, dual task paradigms have higher ecological validity, as most occupations, including sports, require individuals to divide their attention between motor and cognitive tasks (e.g., Register-Mihalik et al., 2013). By not instructing the individual which component to prioritize in a dual task, the individual must decide which component to focus on, leading to an increased cognitive load and potentially eliciting decreased performance in one or both of the components (Register-Mihalik et al., 2013). As such, dual tasks paradigms have greater sensitivity to detect subtle post-concussion impairments than single tasks (e.g., Howell et al., 2017a; Büttner et al., 2020). While dual tasks do have potential for SRC evaluation and management, many of the current paradigms must be completed in laboratories and require expensive equipment and significant expertise to implement and interpret (e.g., Register-Mihalik et al., 2013; Howell et al., 2019). In response to these limitations, Stephens et al., (2018) designed the Dual Task Screen (DTS) as a brief dual task measure that used portable, low-cost equipment and could be administered and scored in fewer than 10 minutes.

Most of the published research in SRC comes from disciplines outside of occupational therapy, including sports medicine, physical therapy, and neurology. I believe that occupational therapy can bring a unique lens to SRC management and serve to enhance an athlete's health, well-being, and occupational performance and participation. Athletes, especially those at high competition levels, likely view sports as a meaningful occupation, if not, their *most* meaningful occupation. Occupational therapists can facilitate athletes' safe return to sports *and* help to prevent occupational deprivation in other occupations (e.g. work, sleep, parenting, etc.) that could be affected by repeat SRC. The DTS, which was designed by an occupational therapist, represents an evaluation measure that aims to be more ecologically valid, as it mimics the behaviors that an athlete must perform during their sport and has potential for use outside of a laboratory setting. Finally, the neuroimaging data that we are collecting during the DTS can enhance the scientific understanding of SRC sequelae, which can inform future evaluation and intervention methods.

1.3 Research Questions

1. Is the Dual Task Screen sensitive to dual task motor costs in healthy, young adult athletes?
2. Is the Dual Task Screen sensitive to dual task cognitive costs in healthy, young adult, athletes?

CHAPTER 2: LITERATURE REVIEW

2.1 Sports-Related Concussion, a Mild Traumatic Brain Injury

Sports-related concussions, or SRC, are a type of mild traumatic brain injury (TBI). TBI results from a direct or indirect biomechanical force to the head, face, neck, or elsewhere on the body that causes linear and/or rotational acceleration of the brain (Herring et al., 2011). TBIs are categorized by severity; this includes mild, moderate, and severe TBI. Known features of a SRC, or mild TBI (mTBI), can include a brief loss of consciousness (≤ 30 minutes), short-term neurological impairment, and functional disturbances (Herring et al., 2011). Acutely, individuals with mTBI can also experience vomiting and dizziness, lethargy, and brief memory loss (Brain Injury Association of America, 2020). In contrast, individuals with moderate TBIs have loss of consciousness for up to 24 hours, overt signs of brain trauma, contusions or bleeding, and positive findings on MRI or CT scans (Brain Injury Association of America, 2020). Finally, individuals with severe TBI have loss of consciousness exceeding 24 hours (i.e. coma) and positive findings on MRI or CT scans (Brain Injury Association of America, 2020).

2.1.1 Incidence of Sports-Related Concussion

In the United States, it is estimated that 1.6 to 3.8 million SRCs occur annually, however this number may be underestimated, as many SRCs are undiagnosed (Cheng et al., 2019; Zuckerman et al., 2015). The incidence of concussion is highest in individuals aged 9 to 22 years old who participate in group athletics (Zuckerman et al., 2015). In a study of SRC in NCAA athletes from 2009-2010 to 2013-2014, researchers found that 1,670 SRCs were reported, of which 888 (53.2%) occurred during competition and 782 (46.8%) occurred during practice (Zuckerman et al., 2015). These reported SRCs represent a national estimate of 10,560 annual SRCs in NCAA athletics (Zuckerman et al., 2015). Sports with the highest number of SRCs included football, men’s ice hockey, and women’s soccer (Zuckerman et al., 2015). Sports with the highest rate of SRCs included men’s wrestling, men’s ice hockey, and women’s ice hockey (Zuckerman et al., 2015).

Consistent with previous findings in NCAA athletes, researchers found that women were at a greater risk for a SRC than men (e.g. Zuckerman et al., 2015). The higher incidence of SRC in females can be contrasted with overall incidence of all severity levels of TBI, which occur more in males than females (Nguyen et al., 2016). In a meta-analysis of sex-based differences in incidences of SRC, researchers found that soccer and basketball elicited statistically significant higher incidence rates of SRC in female athletes than male athletes (Cheng et al., 2019). In addition, the sports of baseball/softball, track and field, and swimming/diving had numerically higher SRC incidence rates in females, but these rates were not statistically significant (Cheng et al., 2019). Researchers hypothesize that higher SRC incidence in females may be due to anatomical differences in females that place them at risk for injury, including weaker neck muscles and greater angular rotation and displacement of the head and neck (Cheng et al., 2019; Zuckerman et al., 2015). These differences may predispose females to greater head-neck acceleration during impacts, which can cause torque that can lead to axonal injuries in the brain, coup injury, or contrecoup injury (Tierney et al., 2005; Barth et al., 2001). If linear acceleration is of sufficient force during impact, the brain may strike the skull in the initial direction of force (coup injury) then rebound to strike the skull in the opposite direction (contrecoup injury) (Barth et al., 2001). In addition to these anatomical differences, studies have found that the mechanism of injury differs between male and female soccer players (Cheng et al., 2019). Female soccer players were more likely to suffer a SRC due to contact with a playing surface or apparatus, such as a soccer ball, while male soccer players were more likely to suffer a SRC due to player-to-player contact (Chandran et al., 2017). These differences in the mechanism of injury may suggest that female and male athletes have different playing styles, which could affect their potential for injury (Chandran et al., 2017).

2.1.2 Diagnostic Criteria for Sports-Related Concussion

The rapid onset and spontaneous recovery of SRC symptoms can make it difficult for athletes, coaches, and physicians to recognize a SRC, which can result in misdiagnosis or underdiagnosis of the concussion (Daneshvar et al., 2011). A comprehensive description of SRC symptoms will be discussed in a later section of this literature review. Proper diagnosis and management of SRC is crucial for safe return-to-play and prevention of repeat SRC (Schatz et al., 2006). Importantly, a history of SRC significantly increases the likelihood of sustaining another SRC (Guskiewicz et al., 2003), and athletes with two or more SRCs have notable cognitive deficits compared to healthy, non-concussed athletes, as well as in comparison to athletes with only one prior SRC (Collins et al., 1999; Moser & Schatz, 2002). Further, long-term complications of repeat SRC may include memory deficits, personality changes, and early onset of dementia (Herring et al., 2011).

If an athlete is suspected of having a SRC, it is recommended that they be removed from gameplay or practice immediately and be evaluated on the sideline by a physician or healthcare provider (Gupta et al., 2019). Following a SRC, a period of acute rest is mandatory to prevent further injury, such as Second Impact Syndrome, long-term disability, and death (Bey & Ostick, 2009; Dziemianowicz et al., 2012). Second Impact Syndrome occurs when an athlete suffers a second head trauma following their sports-related concussion and can result in cerebral edema and brain herniation that can cause death within a few minutes (Bey & Ostick, 2009). Further, this rest period can help ensure that the athlete avoids additional contact, collision, and energy expenditure that could negatively affect recovery (Gupta et al., 2019). In a study of NCAA athletes, individuals who self-recognized symptoms of a SRC and were immediately removed from gameplay recovered more quickly than athletes who continued to play through symptoms (Asken et al., 2018). In addition to removal from activity immediately after a suspected SRC, current treatment protocol recommends rest from physical and cognitive activities (Gupta et al., 2019). Medications can be prescribed to prevent or treat headaches after SRC, but these medications do not expedite the recovery process from SRC (Schneider et al., 2017). After diagnosis of a SRC, most athletes return to "normal" play within several weeks (Gupta et al., 2019). A gradual return-to-play plan should be followed to ensure that an athlete is asymptomatic, able to return to their baseline performance, and safe upon return-to-play (Gupta et al., 2019).

2.2 Return-to-Play Protocols after Sports-Related Concussion

The current gold standard for making return-to-play decisions after a SRC relies on self-reported symptoms, physical examination, and cognitive performance (Phillips & Woessner, 2015). While adults are expected to recover from concussion symptoms within 10 to 14 days, some research has shown that impairments can persist beyond this timeframe, which can impact an individual's health (Riggio & Jagoda, 2016). Approximately 15% of individuals with mTBI have sequelae that persist beyond 3 months and can contribute toward long-term occupational difficulties (Riggio & Jagoda, 2016).

2.2.1 Symptom Evaluation

Symptoms of SRC can be categorized into multiple categories, including cognitive, somatic, affective, and sleep disturbances (Herring et al., 2011). Cognitive symptoms can include confusion, disorientation, and delayed verbal and motor responses (Herring et al., 2011). Somatic symptoms can include headache, dizziness, and visual disturbances (Herring et al., 2011). Affective symptoms include irritability, fatigue, and anxiety, while sleep disturbance symptoms range from sleeping more than usual to sleeping less than usual (Herring et al., 2011). SRC symptom expression and experience can be affected by severity of concussion, comorbidities or pre-morbidities (e.g. mental health disorders), age, and sex (e.g. McCrea et. al, 2013). Individuals who have suffered a SRC often have symptoms across multiple categories, which can affect return-to-play, work, and school (Gupta et al., 2019). Current symptom assessments used in SRC management include the Post-Concussion Symptoms Scale (PCSS), the Rivermead Post-Concussion Symptoms Questionnaire, and Acute Concussion Evaluation (Dziemianowicz et al., 2012). These assessments rely on subjective self-report from athletes to identify the severity of their symptoms on a Likert scale (Dziemianowicz et al., 2012). Additionally, the Modified Glasgow Coma Scale (GCS) is used to rule out more serious brain injury by assessing an athlete's level of consciousness after head injury (Dziemianowicz et al., 2012).

2.2.1 Objective Evaluation

In addition to accurate self-report of symptoms, objective measures are crucial components of the gold standard for return-to-play decisions to ensure the safety of athletes. Objective measurement of SRC includes sensorimotor measures, physiological measures, vestibular-ocular function, and neurocognitive function. The defining factor in recovery from SRC is whether an athlete has regained objective performance that is consistent with pre-injury levels (Collins et al., 2004). Sensorimotor measures include balance, gait, vestibular, and oculomotor analyses, while physiological measures include cardiac autonomic function and sleep assessments (Galea et al., 2018). The Balance Error Scoring System (BESS), which is a component of The Sport Concussion Assessment Tool (SCAT-2), is the most commonly used balance test with athletes (Dziemianowicz et al., 2012). Assessments such as the Buffalo Concussion Treadmill Test (BCTT) can be used to evaluate an athlete's exercise tolerance following a SRC to determine the "threshold" at which their SRC symptoms are aggravated (Leddy et al., 2018). Gupta et al. (2019) emphasize the importance of evaluating vestibular-ocular deficits, which include dizziness, nausea, and visual impairments, as student athletes can exacerbate these in school or work activities; other researchers have also highlighted the importance of related constructs such as visual saccades and convergence (Grady & Master, 2017). Additionally, the King-Devick test can be used to assess impaired eye movement and saccades after SRC (Dziemianowicz et al., 2012). The most prevalent neuropsychological assessment for SRC management is the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT®) Test Battery. The ImPACT® is designed to measure aspects of cognitive functioning, including attention, memory, and reaction time (Lovell et al., 2003). While the ImPACT® has established validity, sensitivity, and specificity (Schatz et al., 2006), it is not recommended as a stand-alone assessment in determining return-to-play in athletes with SRC, as the assessment does not cover all domains that may be affected by a sports-related concussion. Finally, some objective assessments such as The Sport Concussion Assessment Tool (SCAT-2) and the Standardized Assessment of Concussion (SAC) are designed to assess performance across multiple domains, including balance *and* neurocognitive impairment.

2.3 Limitations with Current Sports-Related Concussion Return-to-Play Protocols

While the gold standard for return-to-play decisions includes self-reported symptoms, physical examination, and cognitive performance (Phillips & Woessner, 2015), there are known limitations with evaluation methods - symptom reporting and testing with objective measures -

that are used in clinical practice. Additionally, symptom reporting may be influenced by an athlete's sex, while objective measurement performance may be influenced by an athlete's age.

2.3.1 Limitations with Symptom Reports

Symptom evaluation relies on self-report from an athlete to identify and quantify the symptoms that they are experiencing after a SRC. Symptom scales and checklists – like those described above - rely on athlete honesty, or ensuring that an athlete is accurately reporting their symptoms (Broglio et al., 2017). Subjective symptom scales should not be used alone for SRC evaluation or return-to-play decisions, as they may not accurately identify a concussed athlete or injury recovery (Broglio et al., 2017). SRC evaluation is made more complex by the heterogeneous signs and symptoms that can be associated with a SRC, as individuals experience differing symptoms and recovery trajectories (Howell et al., 2018). Additionally, symptoms of SRC are nonspecific and are similar to other conditions such as anemia, asthma, the flu, and depression (Laker, 2015). The wide range and variability of symptoms can make identification and evaluation of SRC difficult for athletes and providers.

Symptom reports are known to vary depending on an athlete's sex, which could be related to study design or inherent sex differences in reporting behavior or true symptomology. Studies have shown that female athletes are more likely to report symptoms than male athletes (Wallace et al., 2017). Ono et al. (2016) suggest that males may underreport SRC symptoms due to sociocultural constructs and pressure to return-to-play. In addition, research has found that female athletes, compared to males, have increased cognitive, emotional, somatic, and sleep problem symptoms after SRC (Broshek et al., 2005). In studies of sex-based differences in symptoms at baseline (i.e. prior to injury), researchers have found that female athletes reported a higher number of symptoms compared to male athletes (Ono et al., 2016). Additionally, research has shown that female high school and collegiate athletes who sustain a SRC have greater declines in simple and complex reaction times relative to their preseason baseline levels when compared to males (Broshek et al., 2005).

While research on sex-based differences on incidence and initial SRC symptomology have revealed statistically significant differences between female and male athletes, studies of SRC recovery have shown mixed results. Some studies have shown that females have a longer recovery period after SRC (e.g. Kraus et al., 2000; Zuckerman et al., 2014), while other studies show no statistically significant sex-based differences in time-to-symptom recovery (e.g. Brooks et al, 2014; Cantu et al., 2010). These differing results may be due to differences in research methodology, such as prospective versus retrospective study design, heterogeneity of SRC symptoms, and data analyses that fail to control for confounding variables, such as sport and age. While Ono et al. (2016) found no sex-based differences in recovery rate, female athletes had higher rates of symptoms at baseline and during recovery, which, as noted above, may be due to females being more open about symptom reporting than males. In summary, research suggests that sex-based differences in SRC symptomology exist and may be due to differences in symptom sequelae, as well as reporting behaviors.

2.3.2 Limitations with Current SRC Objective Measures

Objective evaluation measures are crucial to include in SRC management, yet there are known limitations with objective evaluation measures used for SRC management and making return-to-play decisions after a SRC. In a study of the test-retest reliability for self-reported SRC symptoms, motor control, and brief and extended neurocognitive assessments, researchers found that the reliability of most SRC assessment tools ranged from 0.30 to 0.72, indicating less than ideal reliability for clinical use (Broglio et al., 2018). Broglio et al. (2018) evaluated mandatory

SRC measures and emerging SRC measures. Mandatory SRC measures included the Standardized Assessment of Concussion (SAC), the Balance Error Scoring System (BESS), and the ImPACT®. Emerging SRC measures included the King-Devick test, the Vestibular Ocular Motor Screen (VOMS), and the Satisfaction with Life Scale (SWLS). While most of the measures included in the study did not meet the reliability scores that are recommended for clinical utility, emerging SRC measures such as the King-Devick test had higher reliability scores (Broglio et al., 2018). Many of the measures generated similar scores between years, suggesting that repeat testing beyond the initial baseline testing did not provide meaningful information to clinicians (Broglio et al., 2018). The findings from this study suggest that repeat testing of athletes on an annual basis using these clinical measures may not provide additional clinical value in SRC management.

Broglio et al. (2018) also note that athletes may not put in an honest effort during SRC testing, whether during baseline testing or testing after SRC. This is crucial, as athletes may intentionally underperform on baseline testing to hide poor post-SRC performance if they are to suffer a SRC (e.g. Leahy, 2011). While the computer-based neurocognitive assessments included in the study by Broglio et al. (2018) had embedded validity checks, it was noted that other assessments did not have validity checks. Validity checks can be used to flag invalid testing data due to intentional underperformance or "sandbagging" on an assessment. Athletes may also demonstrate a learning effect on SRC assessments if they repeat an assessment as a part of their SRC management (Broglio et al., 2018). A reliance on baseline testing can have many effects on SRC management and result in an athlete being cleared to return-to-play before they have fully recovered from their SRC, putting them at risk for further injury.

Age may also play a role in objective behavioral performance in athletes with SRC. For example, high school football players were found to have a different SRC presentation than college football players (Gessel et al., 2007). Specifically, college athletes with SRC had a higher rate of loss of consciousness, but their neuropsychological results matched those of non-concussed athletes sooner than high school athletes (Gessel et al., 2007). In other words, college athletes' neuropsychological performance returned to baseline faster than high school athletes did. While Gessel et al. (2007) did not control for the potential confound of prior concussion history, their results aligned with Fields et al. (2003)'s conclusions, who did control for this variable. Similarly, in a study comparing high school and college football and soccer players, researchers found that high school athletes had a longer neuropsychological recovery period after SRC than college athletes (Field et al., 2003). In a study of gait balance control after SRC, Howell et al. (2015) found that for up to two months post-injury, adolescents with SRC had greater gait balance control deficits than young adults with SRC when compared to healthy, age matched control athletes for both groups. Researchers have hypothesized that the age disparity in SRC recovery may be due to differences in brain and muscle development, including a thinner skull and weaker neck muscles in younger athletes, that can result in a lower threshold for injury (Boden et al., 2007). In addition, external factors, such as the number of medical staff members available for high school versus college athletes, may contribute to the age disparity of SRC recovery (Broglio et al., 2009; Guskiewicz et al., 2003). These age differences are important to consider for SRC evaluation for return-to-play, as assessments and measures used with young athletes should be sensitive enough to detect potentially subtle deficits in behavioral performance.

Along with limitations in test-retest reliability, a reliance on baseline testing, and age-related performance differences, SRC measures used for objective evaluation of athletes may be of insufficient difficulty to detect residual deficits after a SRC. Many of the assessments that are used in SRC management, including the ImPACT®, require an athlete to perform a single motor or cognitive task in the absence of distractors. Thus, these types of single task measures may not be difficult enough to challenge high-performing athletes.

2.4 Research Initiative: Dual Task Paradigms

To address limitations with current SRC evaluation methods, research has focused on the potential of dual tasks for evaluation of athletes. Dual tasks typically require an individual to perform a motor task and a cognitive task simultaneously. Examples of a dual task include walking while reciting the months of the year backwards, or maintaining standing balance with closed eyes while performing subtractions. During a dual task, researchers measure dual task costs, which are defined as poorer motor or cognitive performance during a dual task as compared to single task performance. For example, in a walking or gait task, a dual task cost might look like decreased walking speed while reciting the months of the year backwards as compared to walking speed without a distractor task. Research has shown that the level of complexity of the motor and cognitive tasks included in a dual task paradigm also affects performance. For example, in a study of high school athletes with SRC, Howell et al. (2014) found that as cognitive task complexity increased, gait stability deficits also increased. Specifically, Howell et al. (2014) compared single task performance (walking barefoot) to three separate dual tasks of varying complexity: walking while performing 1) a single auditory Stroop task (least complex task), 2) a multiple auditory Stroop task, and 3) a question-and-answer task (most complex task). As the cognitive task increased in complexity, participants had decreased gait stability (Howell et al., 2014). These results suggest that the inclusion of more complex cognitive tasks may elicit greater motor impairments during dual task paradigms.

Dual task research has also specified which types of lower extremity motor tasks are more difficult or complex for individuals with SRC. Theoretically, gait tasks are considered more challenging than quiet standing tasks for an individual's central nervous system (Winter, 1995). Thus, in a cross-sectional study of adolescent athletes, Howell et al. (2019) hypothesized that a SRC may affect an individual's ability to complete a gait task more than a quiet stance task due to the higher complexity of the motor task. Results from this cross-sectional study supported this hypothesis; participants with a SRC had significantly poorer motor and cognitive performance than control participants, but their performance during a quiet stance task was not as poor (Howell et al., 2019). Howell et al. (2018) also found that the addition of dynamic movements, which increased motor task complexity, enhanced the sensitivity of their dual task paradigms, allowing the researchers to detect subtle deficits in gait speed and cognitive performance in adolescents with a SRC.

2.4.1 Advantages of Dual Task Paradigms

Dual task assessments have higher ecological validity, as most occupations, including playing a sport, require an individual to divide their attention between motor and cognitive tasks (e.g., Register-Mihalik et al., 2013). If an individual is not told which component to prioritize during a dual task, they must decide which component to prioritize, which leads to an increased cognitive load and can cause decreased performance in one or both of the components of the dual task (Register-Mihalik et al., 2013). Researchers have hypothesized that dual tasks may be more sensitive to SRC than single tasks due to the cognitive deficits that are associated with SRC (Register-Mihalik et al., 2013). Register-Mihalik et al. (2013) noted in a systematic review of dual task use for SRC that beyond 6 days post-injury, there was no differentiation between healthy athletes and athletes with SRC who performed a single task paradigm. However, during a dual task paradigm, individuals with SRC displayed a more conservative gait strategy during the dual task (Register-Mihalik et al., 2013). Thus, dual tasks that involve simultaneous cognitive and postural control tasks may be useful in SRC management and evaluation, as they are more reliable than single task paradigms and are better able to detect subtle or residual effects after SRC.

Other research has shown that dual tasks have the potential to detect post-SRC impairments for a longer period than single tasks (e.g., Howell et al., 2017a, 2018; Büttner et al., 2020). Howell et al. (2017a) examined the use of the tandem gait task with one of three cognitive tasks: 1) spelling a five-letter word backwards, 2) serial subtractions, 3), reciting the months in reverse order. Howell et al. (2017a) found when comparing athletes with SRC to healthy control athletes, the dual task conditions were able to detect significantly poorer tandem gait performance in athletes with SRC for up to two weeks post injury, while the single task condition only showed significant group differences at the 72-hour testing trial. In a meta-analysis, Büttner et al. (2020) found that under single task conditions SRC participants walked slower than control participants for up to two weeks post-injury. However, under dual task conditions, these same participants walked slower than control participants for up to two months post-injury (Büttner et al., 2020). This timeline aligns with findings from Howell et al. (2018), who found that dual task paradigms could detect gait balance control impairments between athletes with SRC and healthy athletes during the acute phase of recovery from SRC, as well as at a 2-month follow up test. In comparison, the ImPACT®, a computerized neurocognitive test, did not elicit group differences between athletes with a SRC and healthy athletes at the 2-month follow up test (Howell et al., 2018). Thus, dual task assessments may be more sensitive to lasting residual deficits than traditional neurocognitive tests used for SRC evaluation (Howell et al., 2018). Likewise, a systematic review on single task, dual task, and complex tasks conducted by Fino et al. (2018) found evidence that gait is abnormal during the acute phase after SRC, but resolves over time. While the findings from this systematic review highlighted inconsistencies in the research on gait abnormalities after the acute phase of recovery from SRC (7-10 days after injury), over half of the included studies detected gait abnormalities beyond the acute phase (Fino et al., 2018). These longer-term gait abnormalities were detected using dual task or complex gait tasks, suggesting that dual tasks can provide additional value to SRC management and evaluation (Fino et al., 2018).

2.4.2 Limitations of Dual Task Paradigms

Despite their many advantages, most of the aforementioned dual task paradigms are laboratory intensive and require significant expertise, time, and technology that may not be available in clinical settings (e.g., Register-Mihalik et al., 2013; Howell et al., 2019). Dual task measurement tools often include complex, whole body motion analysis systems, which require multiple cameras and retro-reflective markers placed on participants (e.g., Howell et al., 2019). Other instruments include force platforms, instrumented gait mats, and inertial measurement units (Fino et al., 2018). Further, within SRC research, most dual task paradigms are focused on lower body or lower extremity skills, usually balance or gait. To date, dual task paradigms rarely include upper extremity motor tasks, which are also crucial to playing a sport. Additionally, Fino et al. (2018) found that the majority of research on gait post-SRC is conducted at six laboratories around the world and would likely benefit from expansion to other research labs and disciplines, who may provide differing perspectives on this topic (Fino et al., 2018). Fino et al. (2018) also noted that many of the research studies on dual tasks are conducted with small, homogenous samples, which highlights the need for further high-quality research within this area. In sum, further research on the applicability and feasibility of dual tasks in clinical settings is appropriate and needed to apply research to practice.

2.5 The Dual Task Screen

2.5.1 Development of the Dual Task Screen

Stephens et al. (2018) developed the Dual Task Screen (DTS) to begin addressing the limitations with current dual task paradigms. The DTS was designed to be a portable, low-cost measure that could be administered and scored in fewer than 10 minutes, increasing the clinical feasibility of the measure. Additionally, like other dual task paradigms, the DTS was designed to be a more ecologically valid measure for athletes, as playing sports requires simultaneous motor and cognitive tasks. The original DTS included two dual task paradigms: a Lower Extremity (LE) subtask and an Upper Extremity (UE) subtask. The original DTS was designed to compare single task motor performance to dual task motor performance. Participants completed each subtask as a single motor condition, then as a dual task condition that included a cognitive distractor task.

During the original Lower Extremity (LE) subtask, participants were instructed to walk as quickly as possible for 6-meters, stepping over a yoga block placed 4-meters from the start. In the dual task condition, participants repeated the same LE motor task while simultaneously repeating the months of the year backward. During the original Upper Extremity (UE) subtask, participants were instructed to use alternating hands to throw and catch a tennis ball for 30 seconds while standing 1.5-meters from a wall. In the dual task condition, participants repeated the same UE motor task while simultaneously performing serial 3 subtractions from 100. The motor tasks used in the original DTS were chosen because they were publicly available tasks and had been used in research with adults with mTBI (Cossette et al., 2014 & Wood, 2008). Additionally, the cognitive distractor tasks were selected because they did not require additional equipment or materials, and they took longer to complete than the motor tasks, ensuring dual task conditions throughout the duration of the dual task.

The primary outcome measures for the original DTS were gait speed (meters per second) and number of successful catches. To score each trial, two trained research members viewed video recordings of the trial to calculate gait speed using a manual stopwatch and count the number of successful catches for each participant. Additionally, the trained research members recorded the number of correct months recalled and number of correct subtractions calculated during the dual task conditions. Single task and dual task motor performance was compared for the LE (gait speed) and UE (number of successful catches) subtasks using paired t-tests to determine a dual task cost. In addition, a dual task motor effect (dual task performance/single task performance) was also calculated for each participant to evaluate the percentage of athletes who had a dual task motor cost on the LE and UE subtask.

2.5.2 Pilot Study Findings (Stephens et al., 2018)

In order to examine the prospective utility of the original DTS, Stephens et al. (2018) conducted a pilot study with 32 healthy, adolescent females. The objectives of this pilot study were to: 1) establish the feasibility of using the DTS in a community-based setting, 2) determine the sensitivity of the DTS to dual task motor costs on the LE and UE subtasks in healthy adolescent female athletes. On the LE subtask, group data showed significantly poorer performance (i.e. slower walking speed) on the dual vs. single motor task. Further, 97% of participants had a dual task cost; they walked significantly slower during the dual task condition when compared to the single task condition. On the UE subtask, group data showed significantly poorer performance (i.e. fewer successful catches) on the dual vs. single motor task. Additionally, 88% of participants had a dual task cost; they had significantly fewer catches during the dual task condition when compared to the single task condition. The findings from this pilot study align with other dual task research that has shown that athletes have significantly poorer motor performance during a dual task as compared to a single task. Additionally, the pilot study confirmed that the original DTS could be administered and scored in fewer than 10 minutes in a community setting. The results from this pilot study validated the inclusion of both a LE and UE subtask, as performance in one subtask did not correlate to performance in the other subtask, indicating that these subtasks are measuring different behavioral skills that are relevant to athletic performance.

While this pilot study was successful in determining the feasibility and sensitivity of the DTS, limitations of the measure design were revealed (Aumen et al., 2020). First, gait speed was measured using a manual stopwatch, which can be affected by human error. Additionally, single task versus dual task cognitive performance could not be compared, as a single cognitive trial was not included in the design.

2.5.3 Revisions to the Dual Task Screen (Aumen et al., 2020)

The DTS was revised to address the limitations discovered in the pilot study and to include the capacity to evaluate neural underpinnings of behavioral performance (Aumen et al., 2020). There are three major changes between the original DTS and the revised DTS: 1) addition of smart devices with built-in accelerometers to measure heel strikes and obtain additional and more precise gait data for the LE motor subtasks, 2) modifications to cognitive tasks, and 3) addition of single cognitive trials.

The revised DTS uses smart devices with built-in accelerometers that are strapped to participants' ankles instead of manual stopwatches to collect additional and more precise gait data. Gait performance data now includes gait speed (m/s), total number of steps, average step length (m), average step duration (s), and step duration variability. Modifications were made to the cognitive tasks for both the LE and UE subtasks. In the LE subtask, the cognitive task was changed from a finite task (reciting the months of the year backwards) to an infinite task (verbal fluency). The verbal fluency task required participants to recite as many words as possible that begin with a particular letter (A or F) without repetitions. In the UE subtask, the cognitive task was changed from serial 3's subtractions from 100 to serial 7's subtractions from a given number. These changes were made to increase the cognitive task complexity, making the dual task condition more challenging, in an effort to elicit greater dual task costs (Howell et al., 2014). Finally, a single cognitive trial was added to both the LE and UE subtask in order to compare single and dual task cognitive performance. In addition to changes to address the limitations of the pilot DTS, the revised DTS was used with an older cohort with the goal of replicating pilot study findings in a similar, albeit slightly older, sample of healthy, young adult, female athletes who play contact sports.

While the revised DTS was designed with clinical use in mind, another neuroimaging-compatible version of the DTS using mobile functional near-infrared spectroscopy (fNIRS) was also designed to evaluate the neural underpinnings of single and dual task performance (Aumen et al., 2020). A major difference between the revised DTS and the neuroimaging-compatible version of the DTS is that the neuroimaging-compatible version of the DTS includes a total of 15 trials for both the LE and UE subtasks (5 single motor trials, 5 single cognitive trials, and 5 dual task trials). The addition of multiple trials allows for comparison of test-retest reliability across trials and analysis of the sensitivity of one trial when compared to multiple trials of each task. A major focus of research surrounding SRC is neuroimaging. Neuroimaging has the potential to add another source of evidence to supplement current data used in SRC management. Additionally, advanced neuroimaging techniques can help providers to understand the nature of SRC. While clinical and cognitive symptoms may decrease and return to baseline two weeks after injury, physiological brain measures may remain altered (Dettwiler et al., 2014). Research on neuroimaging is focused on identifying risks for prolonged post-concussive symptoms, long-term cognitive deficits, and appropriate timing for return-to-play (Guenette et al., 2018).

Advanced neuroimaging research has focused on regions of interest (ROI) and shared injury dynamics that are most common to SRC and brain injury (Bigler, 2018). This research is made more complicated by the fact that the mechanism of injury in athletes for SRC can vary in terms of the angle in which the head is struck to cause a SRC (Bigler, 2018). Additionally, many symptoms overlap with other diagnoses, such as depression and post-traumatic stress disorder, which can further complicate clinical assessment (Gunette et al., 2018). There are no clear guidelines for the use of neuroimaging in SRC management (Riggio & Jagoda, 2016).

Advanced neuroimaging techniques used in research include blood oxygenation level dependent (BOLD) functional magnetic resonance imaging (fMRI), which is a noninvasive, repeatable method to measure oxygenated and deoxygenated hemoglobin within the brain (Dettwiler et al., 2014). In studies of neurocognitive tasks such as working memory, attention, and sensory-motor, researchers using fMRI have found that the BOLD signal is altered after SRC (Dettwiler et al., 2014). In an fMRI study comparing four football players with SRC and four football players without SRC, researchers found that there was significantly increased activity in the lateral frontal, superior, and inferior parietal, and bilateral cerebellar regions of the brain within one week after SRC (Jantzen et al., 2004). Researchers did not find significant differences in brain activity between athletes with SRC and those without SRC prior to injury and at one-week post-injury (Jantzen et al., 2004).

Unlike fMRI, functional near-infrared spectroscopy (fNIRS) is an advanced neuroimaging technique that can be used during whole body movements, making it a promising technique for use with athletes. In other words, fNIRS can be used while an athlete is walking, jumping, or even running to evaluate the neural underpinnings of these movements. Research using fNIRS has focused on studying brain activation while performing motor tasks, such as walking, and cognitive tasks, such as verbal fluency (Metzger et al., 2017). Additionally, fNIRS has been proven to be well suited to investigate dual task conditions (e.g., Mirelman et al., 2014; Hermann et al., 2003, 2006). fNIRS measures hemodynamic changes in the cortex using near-infrared light to measure relative changes of oxygenated and deoxygenated hemoglobin.

In an fNIRS study of cortical activation of gait during single and dual task activities, Metzger et al. (2017) had 12 healthy adult females perform three paradigms: 1) slow walk (single task), 2) fast walk (single task), and 3) slow walk and verbal fluency (dual task). During the single task paradigms, Metzger et al. (2017) found that the premotor area of the brain was activated. Metzger et al. (2017) found that the dual task paradigm had more brain activation than either single task paradigm, including Broca's area in the left hemisphere and the corresponding area in the right hemisphere. This may indicate greater involvement of executive functions during the dual task paradigm (Metzger et al., 2017). Other studies have also shown an activation of prefrontal areas in both hemispheres during a dual gait and cognitive task (e.g., Holzer et al., 2006, 2011; Mirelman et al., 2014). These fNIRS studies suggest that dual task paradigms may elicit greater cortical activation than single task paradigms. This supports that dual task paradigms are more difficult that single task paradigms, giving them greater potential for detecting subtle deficits in athletes with SRC. Further, if an athlete does not display a behavior dual task cost, it is possible to detect a neurological difference, as neuroimaging can detect subtle, but meaningful differences, in cortical activation, providing insight into residual deficits from SRC (e.g. Dettwiler et al., 2014).

2.6 Summary and Impact on Current Research

Acquisition of fNIRS data during the neuroimaging-compatible DTS could allow us to contribute to developing understanding of SRC sequelae. Development of the behavioral DTS could serve to improve clinical management of SRC. First, however, it is important to confirm that our DTS can reliably elicit dual task costs in healthy athletes, which is the primary objective of my thesis. Although I did not include fNIRS data in my thesis, I have shared a narrative on how neuroimaging data will be important for continued development and use of the Dual Task Screen. In Chapter 3, I will describe methods used for my thesis and results for female and male participants. Chapter 4 is formatted as an article submission for a peer-reviewed journal based on the data from the female participants only.

CHAPTER 3: THESIS METHODS, RESULTS, & DISCUSSION

3.1 Methods

3.1.1 Participants

Twenty-two healthy, young adult athletes (mean age: 19.50 years old) were recruited using flyers and word-of-mouth via convenience sampling at Colorado State University (see Table 1 for detailed demographic information on the study participants). Participants were excluded if they could not understand English or if they had a condition that prevented them from completing the Dual Task Screen (e.g. inability to throw and catch a ball). Additionally, participants with a history of moderate or severe traumatic brain injury or a history of neurological or psychiatric conditions (e.g. epilepsy, bipolar) were excluded. Prior to participation, participants provided written informed consent; the University's institutional review board approved all study procedures. Participants received nominal monetary compensation for completing the study.

Table 3.1

Subject Demographics

Subject	Sex	Age	Sport	# Previous SRC
1	F	21	Soccer	0
2	F	20	Soccer	2
3	F	21	Soccer	1
4	F	21	Ice Hockey	1
5	F	21	Ice Hockey	0
6	F	20	Ice Hockey	1
7	F	20	Ice Hockey	0
8	F	20	Ice Hockey	0
9	M	21	Ice Hockey	1
10	F	19	Soccer	0
11	M	16	Football	1
12	F	19	Ice Hockey	1
13	F	19	Ice Hockey	0
14	F	19	Ice Hockey	0
15	F	19	Lacrosse	1
16	F	19	Ice Hockey & Lacrosse	1

17	F	18	Ice Hockey	1
18	F	18	Water Polo	1
19	M	17	Football	0
20	F	22	Track & Field	0
21	F	21	Track & Field	0
22	F	18	Track & Field	0

Note. Participants reported their sports-related concussion (SRC) history. All SRCs occurred >6 months prior to participation in the research study.

3.1.2 Procedure

Behavioral data were collected in a single research laboratory visit. Participants performed the revised Dual Task Screen (described below) in an empty, quiet hallway. Each session was videotaped so that scoring could be completed by the research team.

3.1.3 Revised Dual Task Screen

Similar to the original DTS, the revised DTS includes a Lower Extremity (LE) and Upper Extremity (UE) subtask. While each subtask in the original DTS included two conditions, the revised DTS has three conditions per subtask that are performed in the following order: one single motor condition, one single cognitive condition (new addition to the revised DTS), and one dual task condition. In the original DTS, motor task performance was the primary outcome measure in the single and dual task conditions. With the addition of a single cognitive condition, the revised DTS can evaluate both motor *and* cognitive task performance during the single and dual task conditions. The revised DTS has two other major modifications from the original DTS. First, the cognitive task for the LE subtask was changed from a finite response task (reciting months backwards) to an infinite response task (verbal fluency). Second, iPod-based accelerometers were used during the LE subtask to acquire detailed gait data and reduce measurement error. Specific features of both subtasks are described below. Table 2 includes the primary outcome measures for each subtask.

Revised DTS: LE Subtask

The single motor condition is an 18-meter obstacle walk. Prior to this condition, participants are fitted with iPods that are attached to each ankle, as the iPods have built-in accelerometers that permit acquisition of detailed gait performance data. During the condition, participants walk as quickly as possible for 18 meters while stepping over three yoga blocks placed 4.5 meters apart along the walkway. The single cognitive condition is a verbal fluency task. During this condition, participants state as many words as they can that begin with a particular letter (A or F) without repetitions. Participants are given the same amount of time for the single cognitive condition as it took them to walk the 18-meter obstacle course during the single motor condition. In the dual task condition, participants simultaneously performed the obstacle walk and verbal fluency tasks. The primary outcome measure for the single motor and dual task conditions is gait speed measured in meters/second (m/s). Secondary outcome measures for the single motor and dual task conditions include number of total steps, average step length (meters), average step duration (seconds), and step duration variability. The outcome measure for the single cognitive and dual task conditions is the total number of unique words produced.

Revised DTS: UE Subtask

The single motor condition is an alternating hand wall toss-task. During the condition, participants stand 1.5 meters from a wall and throw and catch a tennis ball using alternating hands for 30 seconds. For successful catches, a participant had to throw the tennis ball underhanded with one hand and catch it with their other hand without the ball hitting the ground (either underhand or overhand). The single cognitive condition is a serial 7 subtraction task. During this condition, participants serially subtracted by 7s from a given number (100 or 150) for

30 seconds. In the dual task condition, participants simultaneously performed the alternating hand wall toss- task serial 7 subtractions for 30 seconds. The outcome measure for the single motor and dual task conditions is the total number of catches. The outcome measure for the single cognitive and dual task conditions is the total number of correct subtractions.

Table 3.2

Primary Outcome Measures from the Revised Dual Task Screen

Subtask	Condition	Primary Outcome Measure
Lower Extremity	Motor (Obstacle Walk)	Gait Speed (m/s)
	Cognitive (Verbal Fluency)	Total # of Words Produced (no repeats)
Upper Extremity	Motor (Wall Toss Task)	Total # of Catches
	Cognitive (Serial 7 Subtractions)	Total # of Correct Subtractions

3.1.4 Scoring of the Revised Dual Task Screen

To score the cognitive conditions and UE motor conditions, two trained research assistants viewed and scored all video recordings to achieve a consensus on all outcome measures. If the research assistants did not reach consensus, the video was re-watched until consensus was reached.

LE Subtask Scoring

LE data for the single motor and dual task conditions were collected using iPod-based accelerometers that were attached to participants' ankles during the subtask. Gait performance data were collected by running the Sensor Data application (Wavefront Labs). Data from the right and left legs were wirelessly transferred to a computer and merged into one time-aligned Spike 2 (Cambridge Electronic Design Limited) data file for analysis by a trained research assistant to calculate secondary outcome measures*. For the LE single cognitive and dual task conditions, videotape recordings were watched to determine the total number of words that the participant was able to produce during the allotted time. Repeated words were not counted.

**Note to committee – we will be including more detail on these steps for the peer-reviewed manuscript prior to submission, but Kalena was not involved in this data analysis.*

UE Subtask Scoring

For the UE single motor and dual task conditions, video recordings were watched to determine the number of successful catches. A successful catch was counted if the participant threw the ball underhanded and caught it with their other hand (either overhand or underhand). If the ball hit the ground, this was not counted as a catch, but if the ball bounced off the participant's arm or trunk and was subsequently secured in his/her hand, this counted as a successful catch. For the UE single cognitive and dual task conditions, videotape recordings were watched to determine the total number of correct subtractions. If a participant made a subtraction error but then correctly subtracted 7, only one error was counted (e.g., 150, 144, 137 would count as one error and one correct subtraction).

3.1.5 Statistical Analysis

Our research objectives are twofold: establish if the revised DTS is sensitive to 1) dual task *motor* costs, and 2) dual task *cognitive* costs. Descriptive statistics were be used to summarize group data for the single and dual tasks. To determine if the revised DTS is sensitive to dual task motor costs, we used a one-tailed paired t-test to compare single and dual *motor* performance for the LE and UE subtasks. A one-tailed test was chosen as we hypothesized that participants would have worse performance under dual task conditions when compared to single task conditions. Additionally, we calculated a dual task motor effect (dual task performance/single task performance times 100) for each participant to evaluate the percentage of athletes who had a dual task motor cost on the LE or UE subtask. For the motor outcome measures of gait speed, step length, and total number of catches, if a dual task effect was greater than 100%, the participant had better performance during dual task conditions. Conversely, if a dual task effect was less than 100% for these outcome measures, the participant had poorer performance during dual task conditions. For the secondary LE motor outcome measures of total number of steps, step duration, and step duration variability, if a dual task effect was less than 100%, the participant had better performance during dual task conditions. Conversely, if a dual task effect was greater than 100% for these outcome measures, the participants had poorer performance during dual task conditions. To determine if the revised DTS is sensitive to dual task cognitive costs, we also used a one-tailed paired t-test to compare single and dual *cognitive* performance for the LE and UE subtasks. We also calculated a dual task cognitive effect for each participant to evaluate the percentage of athletes who had a dual task cognitive cost on the LE or UE subtask. Statistical significance for all one-tailed paired t-tests was set at $p < 0.0125$ (.05/4) to account for multiple comparisons. Finally, each participant's dual task effects from the LE and UE subtasks was evaluated to determine if the participant had a dual task motor or cognitive cost on the revised DTS. A dual task cost on either the LE or UE motor tasks represented that the revised DTS elicited, or was sensitive to, dual task motor costs. Similarly, a dual task cost on either the LE or UE cognitive tasks represented that the revised DTS elicited, or was sensitive to, dual task cognitive performance. The percentage of participants who have a dual task motor cost was calculated for each subtask, as well as the percentage of participants who had a dual task cognitive cost for each subtask. Additionally, the percentage of participants who had a dual task motor cost on either or both the LE or UE subtask was calculated to determine the sensitivity of parallel administration, or administration of both the LE and UE subtask, of the DTS. Similarly, the percentage of participants who had a dual task cognitive cost on either or both the LE or UE subtask was calculated to determine the sensitivity of parallel administration of the DTS.

3.2 Results

3.2.1 Dual Task Motor Costs

One-tailed paired t-tests were used to determine if the revised DTS was sensitive to dual task motor costs. Statistically significant differences were observed between single-condition and dual-condition motor performance on both the LE and UE subtasks. In the LE subtask, participants walked significantly slower during the dual task condition (M = 1.51 m/s, SD = 0.24) than the single task condition (M = 1.73 m/s, SD = 0.21), $t(21) = 6.846$, $p < 0.001$, $d = 1.458$ (Figure 1A). Additionally, statistically significant differences were observed for all secondary motor outcome measures from the LE subtask (see Table 3. In the UE subtask, participants had significantly fewer catches during the dual task condition (M = 15.55, SD = 3.76) than the single task condition (M = 19.32, SD = 4.15), $t(21) = 4.263$, $p < 0.001$, $d = 0.909$ (Figure 1B).

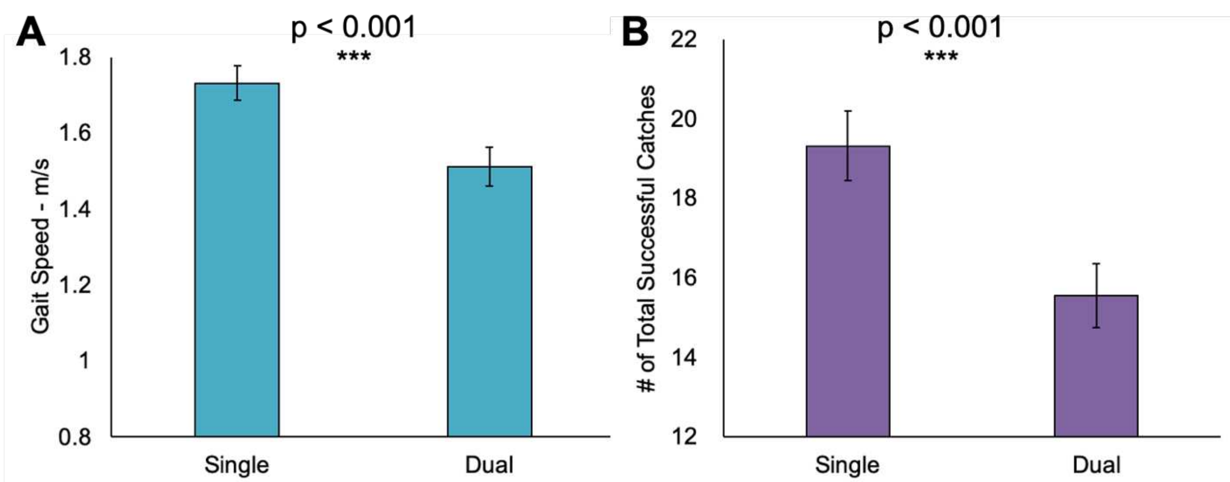

Figure 3.1. Single versus dual condition performance: primary motor outcome measures. Both the Lower Extremity (A) and Upper Extremity (B) subtasks elicited poorer dual-condition motor performance; significant differences in performance were observed between single and dual task conditions. Error bars represent the standard error. Asteriks (*) represent the significance level; *** represents a p-value < 0.001.

Table 3.3

Secondary Outcome Measures: LE Motor Task (Obstacle Walk)

Secondary Outcome Measure	Single Mean	Single SD	Dual Mean	Dual SD	*p*	*t*	*d*
Total # of Steps	22.64	2.06	24.05	2.26	< 0.001	-4.499	0.960
Avg. Step Length (meters)	0.80	0.07	0.76	0.07	< 0.001	4.383	0.934
Avg. Step Duration (seconds)	0.49	0.05	0.53	0.05	< 0.001	-4.980	1.063
Step Duration Variability	0.08	0.07	0.10	0.10	0.002	-3.418	0.728

A dual task effect (dual task performance/single task performance) was calculated to determine the percentage of athletes who had a dual task motor cost on the LE and UE subtasks (Figures 2 and 3). When analyzing the primary LE motor task outcome measure only (gait speed), the LE motor task elicited a dual task cost in 86% of participants. Three participants, or 14%, walked faster (M = 0.04 m/s) during the dual task condition when compared with the single task condition. The dual task effect for the LE motor task ranged from 72.5% (minimum) to 105.9% (maximum). When analyzing the secondary LE motor task outcome measures, the LE motor task elicited a dual task cost in 68% of participants for two of the outcome measures: number of total steps and step length. For the secondary outcome measure of step duration, the LE motor task elicited a dual task cost in 86% of participants. When analyzing step duration variability, the LE motor task elicited a dual task cost in 95% of participants. The UE motor task elicited a dual task cost in 73% of participants. Four participants, or 18%, had 1-4 more catches (M = 2.25) during the dual task condition when compared to the single task condition, while two participants, or 10%, had the same number of catches on both task conditions. The dual task effect for the UE motor subtask ranged from 47.8% (minimum) to 133.3% (maximum). Parallel administration of the LE and UE motor tasks rendered 95% sensitivity in detecting poorer dual task motor performance. In other words, 95% of participants had a dual task cost on either the LE or UE motor tasks.

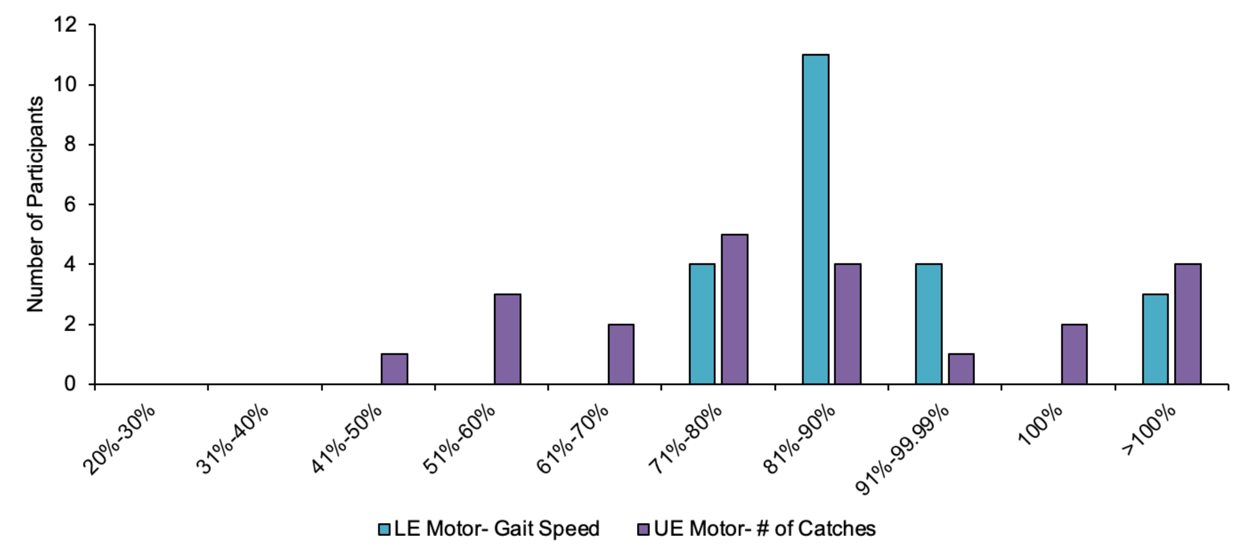

Figure 3.2. Dual task motor effects: primary outcome measures. The range of dual task motor effects (dual task motor performance/single task motor performance, represented as a percentage) for the Lower Extremity and Upper Extremity subtasks. Parallel administration of both subtasks rendered 95% sensitivity in detecting poorer dual task motor performance.

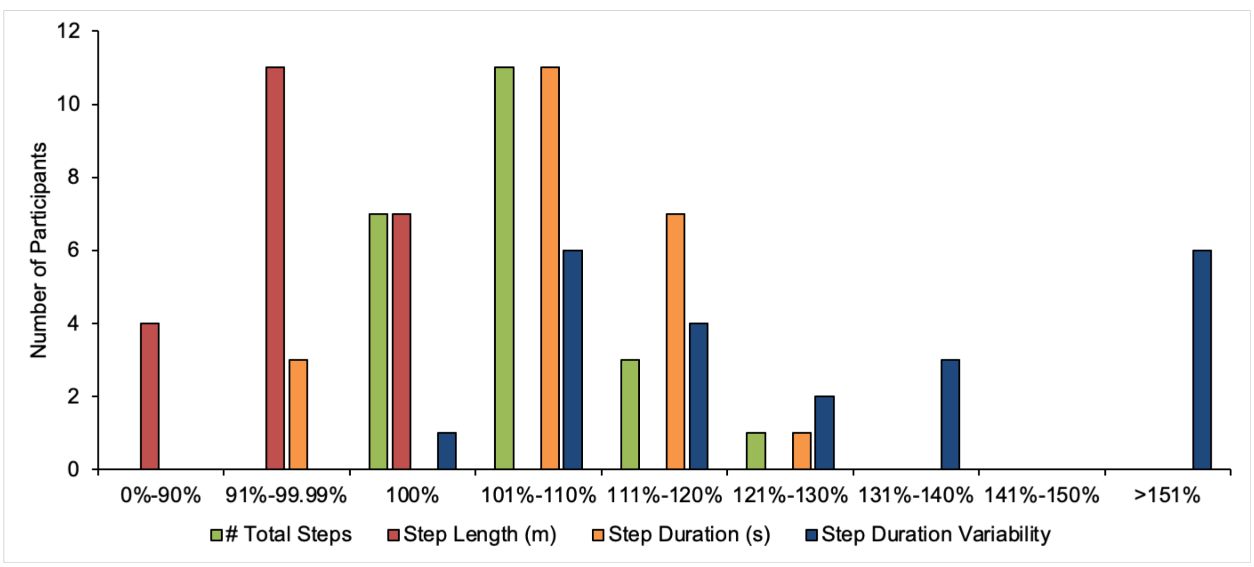

Figure 3.3. Dual task motor effects: secondary LE motor outcome measures. The range of dual task motor effects (dual task motor performance/single task motor performance, represented as a percentage) for the Lower Extremity secondary motor outcome measures. For # total steps, step

duration, and step duration variability, a dual task effect greater than 100% represents poorer performance during the dual task compared to the single task.

3.2.2 Dual Task Cognitive Costs

One-tailed paired t-tests were used to determine if the revised DTS was sensitive to dual task cognitive costs. While numerical differences were observed between single-condition and dual-condition cognitive performance on the LE subtask, these differences failed to meet the test-wise criteria for significance ($p = 0.0125$). In the LE subtask, participants produced fewer words during the dual task condition ($M = 5.50$, $SD = 2.16$) than the single task condition ($M = 6.18$, $SD = 2.13$, $t(21) = 1.460$, $p = 0.079$, $d = 0.311$ (Figure 4A). Statistically significant differences were observed between single-condition and dual-condition cognitive performance for the UE subtask. In the UE subtask, participants had significantly fewer correct subtractions ($M = 5.96$, $SD = 3.85$) than the single task condition ($M = 7.23$, $SD = 3.83$), $t(21) = 2.846$, $p = 0.005$, $d = 0.607$ (Figure 4B).

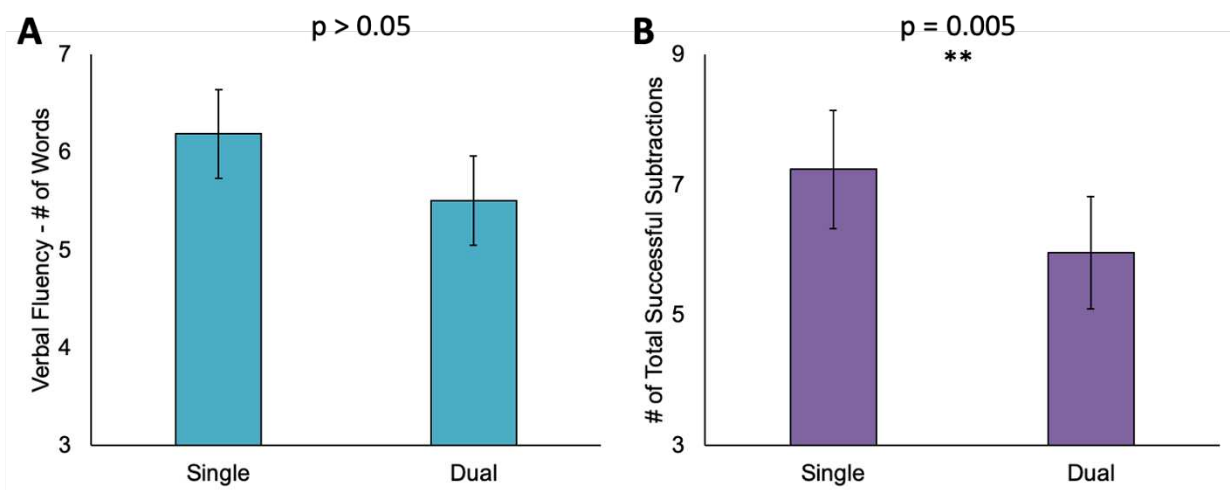

Figure 3.4. Single versus dual condition performance: cognitive outcome measures. Both the Lower Extremity (A) and Upper Extremity (B) subtasks elicited poorer dual-condition cognitive performance. Numerical differences in performance were observed between the Lower Extremity single and dual task conditions; significant differences in performance were observed between the Upper Extremity single and dual task conditions. Error bars represent the standard error. Asteriks (*) represent the significance level ; ** represents a p-value < 0.01.

A dual task effect (dual task performance/single task performance) was calculated to determine the percentage of athletes who had a dual task cognitive cost on the LE and UE subtasks (Figure 5). The LE cognitive task elicited a dual task cost in 55% of participants. Five participants, or 23%, produced 1-5 more words during the dual task condition (M = 2.00) than the single task condition, while five participants, or 23% produced the same number of words on both task conditions. The dual task effect for the LE cognitive task ranged from 37.5% (minimum) to 225.0% (maximum). The UE cognitive task elicited a dual task cost in 68% of participants. Seven participants, or 32%, were able to correctly subtract 1-2 more numbers (M = 1.29) during dual task conditions than single task conditions. The dual task effect for the UE cognitive task ranged from 20.0% (minimum) to 300.0% (maximum). Parallel administration of the LE and UE cognitive tasks rendered 82% sensitivity in detecting poorer dual task cognitive performance.

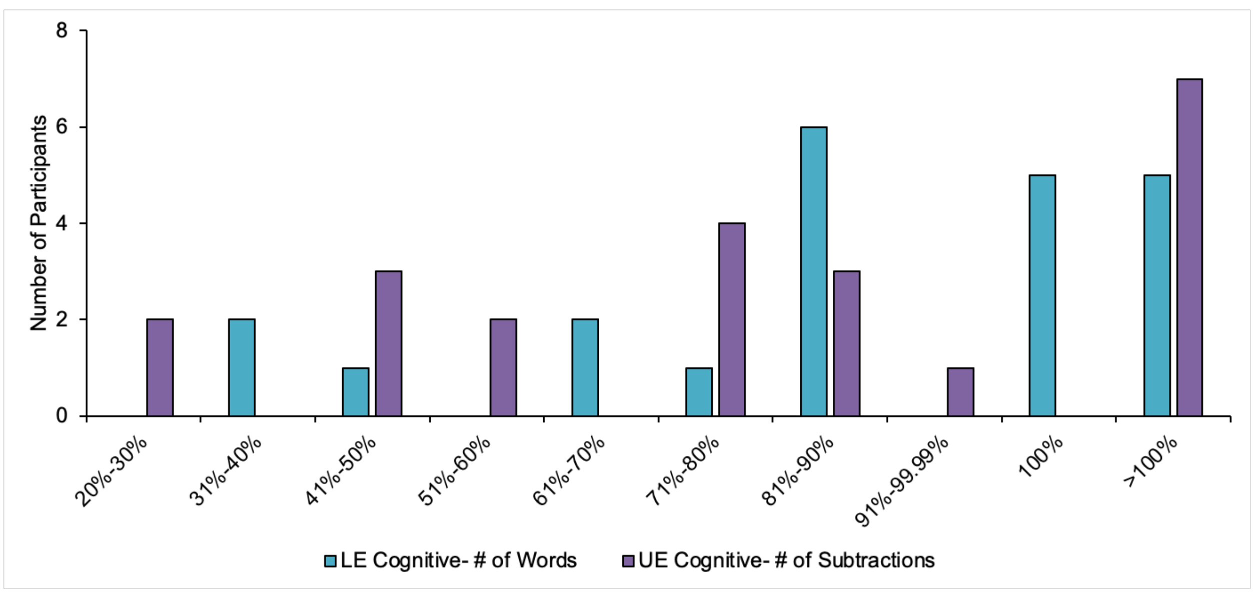

Figure 3.5. Dual task cognitive effects. The range of dual task cognitive effects (dual task cognitive performance/single task cognitive performance, represented as a percentage) for the Lower Extremity and Upper Extremity subtasks. Parallel administration of both subtasks rendered 82% sensitivity in detecting poorer dual task cognitive performance.

3.3 Discussion

This study had two main research objectives: 1) replicate pilot study findings and demonstrate that the revised DTS is sensitive to dual task motor costs in healthy, young adult athletes, 2) determine if the revised DTS is sensitive to dual task cognitive costs in healthy, young adult athletes. This study addressed many of the limitations found in the pilot study of the original DTS, such as the inability to evaluate dual task cognitive costs and the lack of precision germane to using manual stopwatches (Stephens et al., 2018). Additionally, we were able to replicate the results from the pilot study with an older cohort of healthy, young adult athletes. We were able to test 22 participants and established that the revised DTS could be administered with each participant in fewer than 10 minutes, even with the addition of a single cognitive trial and the use of smart devices for the LE trials. Importantly, the addition of smart devices allowed us to gather more precise and sensitive gait data without substantial increases in cost or time of administration when compared to the original DTS. This makes the revised DTS a viable screening measure for clinical use, as it is time efficient, low cost, and portable.

As in our previous work (Stephens et al., 2018), we observed significant dual task motor costs (i.e. significantly poorer performance on dual trials compared to single trials) on both the LE and UE subtasks for all outcome measures. The use of iPod-based accelerometers during the LE subtask allowed us to collect and analyze gait data that was not collected during the pilot study. We also found that the revised DTS was able to elicit a dual task motor cost in the majority of participants, although a few participants failed to demonstrate poorer dual task motor performance.

We found that the revised DTS elicited numerical dual task cognitive costs (i.e. poorer cognitive performance on the dual trials compared to the single trials) on both the LE and UE subtask, but only the UE subtask elicited performance differences that were statistically significant. Similar to the dual task motor effect, we also found that the revised DTS was able to elicit a dual task cognitive cost in the majority of participants. However, these results suggest that cognitive performance – as we measured it - was less susceptible to dual task interference than motor performance. This might be due to greater variability in cognitive task performance, as compared to motor task performance, particularly since we evaluated gait speed which is known to be consistent (Middleton et al., 2015). Alternatively, cognitive tasks may be more disruptive to motor performance than motor tasks are to cognitive performance. Finally, it is possible that most participants chose to prioritize cognitive performance over motor performance, thereby rendering more consistent cognitive performance between single and dual conditions with much poorer motor performance. These potential explanations should be tested with future research studies, which can use multiple trials or testing sessions to evaluate the consistency of dual task motor and cognitive costs.

The findings from this study align with current research surrounding the use of dual task paradigms in SRC management. Research using dual task paradigms has shown that dual tasks can elicit poorer dual task motor performance in adolescent and young adult athletes (e.g. Howell et al., 2017a; Büttner et al., 2020). Importantly, many of these studies do not include cognitive outcome variables, and instead focus on motor outcomes. Our results demonstrate that future dual task studies may benefit from inclusion of potential dual task cognitive costs to better understand their influence on dual tasks and potential for use with SRC management. Additionally, most research on dual task paradigms has focused on lower body or lower extremity motor skills; our study adds to the growing body of research by including a subtask that involves upper extremity motor skills.

3.4 Limitations & Future Directions

There are some limitations of the current study. While most of the participants in this study exhibited a dual task cost, or poorer dual task motor or cognitive performance, some participants had better dual task performance when compared to single task performance. These results may be due to the complexity of the motor and cognitive tasks included in the revised DTS, as motor and cognitive abilities may be influenced by the difficulty of the task. Prior research has shown that the complexity of the cognitive task used during a dual task can influence motor performance (Howell et al., 2014; Patel et al., 2014). Patel et al. (2014) found that verbal fluency and serial subtraction tasks elicited similar dual task motor costs, which may suggest that these tasks require similar cognitive demands to complete. Verbal fluency tasks require an individual to use semantic memory, while serial subtraction tasks challenge working memory. More complex cognitive tasks, such as a visual Stroop task, may involve executive function and information processing speed, which require a higher cognitive demand (Patel et al., 2014). Future iterations of the DTS can consider using tasks of greater complexity to attempt to elicit a dual task cost across all participants.

Another limitation of the current study was the number of trials included in the revised DTS. Participants completed the revised DTS in a particular trial order (single motor trial, single cognitive trial, dual task trial); thus, practice effects could have influenced a participant's motor and cognitive performance. This potential practice effect may be mitigated by having participants perform multiple trials of each trial type in a random order, which could result in more consistency in eliciting dual task costs.

Finally, the small, homogenous sample included in this study limits the generalizability of the findings. Further data collection from athletes across age, sex, sports, and competition level can improve our understanding of the sensitivity of the DTS. Future research with the DTS will also include athletes with sports-related concussion to test the specificity of the DTS to concussion-induced deficits. Additionally, a neuroimaging compatible version of the DTS has been created to understand the neural underpinnings of the motor and cognitive data collected while a participant is performing a single task compared to a dual task. The neuroimaging compatible version of the DTS also includes multiple trials of each trial type (single motor, single cognitive, and dual motor/cognitive) which may, as noted earlier, reduce or eliminate practice effects elicited by the revised DTS.

3.5 Implications for Occupational Therapy Practice

The findings of this study have the following implications for occupational therapy practice:

- Occupational Therapists (OTs) can provide distinct value by bringing a holistic, occupation-focused lens to SRC management. Having a comprehensive understanding of SRC sequelae can help to inform OT intervention and evaluation in athletes with SRC. By using assessments that are able to detect subtle behavioral or neurological deficits, OTs can better target interventions and evaluation strategies to ensure that they address these factors.
- SRCs can result in residual or subtle deficits that may not be found using traditional concussion assessments. Dual task assessments represent occupationally-based measures, as they attempt to mimic the occupational demands of playing a sport (i.e. simultaneous motor and cognitive tasks). Dual task assessments may be useful in making safer return-to-play decisions, ensuring an athlete's safety not only in their chosen sport, but across other meaningful occupations.

- Athletes represent a model population to study brain injury, as they are an accessible population for understanding this injury.

3.6 Conclusion

Dual task paradigms, such as the revised DTS, could potentially address limitations of SRC management, particularly insufficient difficulty of currently-used measures. Dual task paradigms may be able to help clinicians and providers involved in SRC management make safer return-to-play decisions, which is crucial to the health of athletes of all ages. The results from our study indicate that the revised DTS is a promising measure for use in SRC management and has been demonstrated to be sensitive to dual task motor and cognitive costs in healthy young adult athletes. Future research will focus on the use of multiple trials to better understand potential practice effects, as well as the complexity of cognitive and motor tasks included in the DTS. Additionally, a neuroimaging-compatible version of the DTS will allow us to examine the neural underpinnings of the behavioral data collected using the DTS. Future studies with the DTS will help us to develop a clinically valid measure that can be used with athletes after SRC.

CHAPTER 4: PROSPECTIVE MANUSCRIPT & METHODS[1]

4.1 Introduction

Sports-related concussion, or SRC, is a form of mild traumatic brain injury (mTBI) that can result in short-term and long-term functional impairments (e.g. Gupta et al., 2019). In the United States, it is estimated that 1.6 to 3.8 million SRCs occur annually, however this number may be underestimated as many SRCs are undiagnosed (e.g. Cheng et al., 2019). Notably, the incidence of concussion is highest in individuals aged 9 to 22 years old who participate in group athletics (Zuckerman et al., 2015). Additionally, research has shown that women are at a greater risk for sustaining SRC compared to men, despite overall TBI incidence being higher in males (e.g. Zuckerman et al., 2015, Nguyen et al., 2016). Further, athletes with a history of sustaining a SRC have an increased likelihood of suffering another SRC upon return to their sport (Guskiewicz et al., 2003).

SRC can affect an athlete's performance and participation in their sport, and negatively influence other occupational domains, including work, school, rest, and sleep (AOTA, 2020; Gupta et al., 2019). Proper diagnosis and management of SRC in athletes is crucial to ensure their health and safety for return-to-play. The current gold standard for return-to-play decision-making after a SRC uses self-reported symptoms, physical examination, and cognitive performance (Phillips & Woessner, 2015). Despite the existence of a gold standard, most SRC providers rely solely on symptom reports and do not incorporate other components of this standard (Haider et al., 2018).

[1] Note: Chapter 4 is written as prospective manuscript (abstract not yet included) for submission to the American Journal of Occupational Therapy (AJOT). Data from female participants only is included in this section. Thesis style numbering will be removed prior to journal submission and additional detail will be added regarding accelerometer data analysis.

Objective measures that are currently used in SRC management have limitations, including poor test-retest reliability, reliance on baseline testing, and insufficient difficulty for high-performing athletes (Broglio et al., 2017; Broglio et al., 2018, Howell et al., 2019). To address limitations surrounding insufficient difficulty, recent research has focused on developing dual tasks paradigms for athletes with SRC. Dual tasks paradigms are more difficult than tasks used in current SRC evaluation, as they require individuals to perform a motor task and distractor task (often a cognitive task), simultaneously. Subsequently, dual task paradigms have higher ecological validity, as most occupations, including sports, require individuals to divide their attention between motor and cognitive tasks (e.g., Register-Mihalik et al., 2013). As such, dual tasks paradigms may have greater potential to detect post-concussion impairments for a longer duration than single tasks (e.g., Howell et al., 2017a; Büttner et al., 2020). A primary outcome of most dual task paradigms is a dual task cost, which is defined as reduced dual task performance as compared to single task performance.

While dual tasks have been shown to have potential benefit for SRC management, many dual task measures require expensive and cumbersome laboratory equipment, such as motion capture systems. The Dual Task Screen (DTS), was designed to be used with portable, low-cost materials, improving its potential for use outside of a laboratory setting. This study expanded upon a previous pilot study of the DTS, which was conducted with 32 healthy, female adolescents (Stephens et al., 2018). The original DTS, which was designed by an occupational therapist, represents an evaluation measure that aims to be more ecologically valid, as it more-closely mimics the environmental demands that an athlete experiences during their sport. The DTS was designed to evaluate lower extremity (LE) motor skills - gait - and upper extremity (UE) motor skills - hand-eye coordination - that are commonly required in sports. The findings from the pilot study aligned with other dual task research; athletes had significantly poorer motor performance during dual task components of the DTS, compared to their performance on single tasks. Additionally, the pilot study confirmed that the original DTS could be administered and scored in fewer than 10 minutes, using low-cost portable materials in a community setting. The results from this pilot study also supported the inclusion of both a LE and UE subtask, as performance in one subtask did not correlate to performance in the other subtask, indicating that these subtasks are measuring different behavioral skills that are relevant to athletic performance.

Despite these promising findings, limitations of the original DTS measure design were revealed. First, gait speed was measured using a manual stopwatch, which lacks precision and is prone to human error. Additionally, single versus dual task cognitive performance could not be compared, as a single cognitive trial was not included in either the LE or UE subtask. To address these limitations, a revised version of DTS was created (Aumen et al., 2020).

The present study uses the revised DTS and has two main research objectives. First, we seek to replicate pilot study findings and demonstrate that the revised Dual Task Screen is sensitive to dual task motor costs in healthy, *young adult* female athletes. Secondly, we seek to determine if the revised Dual Task Screen is sensitive to dual task *cognitive* costs in healthy, young adult female athletes. The participants in this study represent an older cohort as compared to the pilot DTS study in order to evaluate the use of the measure with a different age group, as research has shown that motor performance is affected by an athlete's age (e.g. Howell et al., 2015). We hypothesized that participants would have significant dual task costs (i.e., poorer motor and cognitive performance under dual task conditions compared to single task conditions). We also controlled for age and sex by limiting our analysis to young adult, female athletes, although future research will include adolescent and young-adult male athletes.

4.2 Methods

4.2.1 Participants

Nineteen healthy, young adult female athletes (mean age: 19.74) were recruited using flyers and word-of-mouth via convenience sampling at Colorado State University. Participants were excluded if they could not understand English, or if they had a condition that prevented them from completing the Dual Task Screen (e.g. inability to throw and catch a ball). Additionally, participants with a history of moderate or severe traumatic brain injury or a history of neurological or psychiatric conditions (e.g. epilepsy, bipolar) were excluded. Four participants played soccer, nine played ice hockey, one played lacrosse, one played both lacrosse and ice hockey, one played water polo, and three competed in track and field. None of the athletes had sustained a concussion within the last six months, but nine participants had a history of sports-related concussion. The University's institutional review board approved all study procedures, and prior to participation, participants provided written informed consent. Participants received nominal monetary compensation for completing the study.

4.2.2 Procedure

Behavioral data were collected in a single research laboratory visit. Participants performed the revised Dual Task Screen (described below) in an empty, quiet hallway, and performance was videotaped so that scoring could be completed by the research team.

4.2.3 Revised Dual Task Screen

Similar to the original DTS, the revised DTS includes a Lower Extremity (LE) and Upper Extremity (UE) subtask. While each subtask in the original DTS included two conditions, the revised DTS has three conditions per subtask that are performed in the following order: one single motor condition, one single cognitive condition (new addition to the revised DTS), and one dual task condition. In the original DTS, motor task performance was the primary outcome measure in the single and dual task conditions. With the addition of a single cognitive condition, the revised DTS can evaluate both motor *and* cognitive task performance during the single and dual task conditions. The revised DTS has two other major modifications from the original DTS. First, the cognitive task for the LE subtask was changed from a finite response task (reciting months backwards) to an infinite response task (verbal fluency). Second, iPod-based accelerometers were used during the LE subtask to acquire detailed gait data and reduce measurement error. Specific features of both subtasks are described below. Table 1 includes the primary outcome measures for each subtask.

Revised DTS: LE Subtask

The single motor condition is an 18-meter obstacle walk. Prior to this condition, participants are fitted with iPods that are attached to each ankle, as the iPods have built-in accelerometers that permit acquisition of detailed, sensitive gait performance data. During the condition, participants walk as quickly as possible for 18 meters while stepping over three yoga blocks placed 4.5 meters apart along the walkway. The single cognitive condition is a verbal fluency task. During this condition, participants state as many words as they can that begin with a particular letter (A or F) without repetitions. Participants are given the same amount of time for the single cognitive condition as it took them to walk the 18-meter obstacle course during the single motor condition. In the dual task condition, participants simultaneously performed the obstacle walk and verbal fluency tasks. The primary outcome measure for the single motor and dual task conditions is gait speed measured in meters/second (m/s). Secondary outcome measures for the single motor and dual task conditions include number of total steps, average step length (meters), average step duration (seconds), and step duration variability. The outcome measure for the single cognitive and dual task conditions is the total number of unique words produced.

Revised DTS: UE Subtask

The single motor condition is an alternating hand wall toss-task. During the condition, participants stand 1.5 meters from a wall and throw and catch a tennis ball using alternating hands for 30 seconds. For successful catches, a participant had to throw the tennis ball underhanded with one hand and catch it with their other hand without the ball hitting the ground (either underhand or overhand). The single cognitive condition is a serial 7 subtraction task. During this condition, participants serially subtracted by 7s from a given number (100 or 150) for 30 seconds. In the dual task condition, participants simultaneously performed the alternating hand wall toss- task serial 7 subtractions for 30 seconds. The outcome measure for the single motor and dual task conditions is the total number of catches. The outcome measure for the single cognitive and dual task conditions is the total number of correct subtractions.

Table 4.1

Primary Outcome Measures from the Revised Dual Task Screen

Subtask	Condition	Primary Outcome Measure
Lower Extremity	Motor (Obstacle Walk)	Gait Speed (m/s)
	Cognitive (Verbal Fluency)	Total # of Words Produced (no repeats)
Upper Extremity	Motor (Wall Toss Task)	Total # of Catches
	Cognitive (Serial 7 Subtractions)	Total # of Correct Subtractions

4.2.4 Scoring of the Revised Dual Task Screen

To score the cognitive conditions and UE motor conditions, two trained research assistants viewed and scored all video recordings to achieve a consensus on all outcome measures. If the research assistants did not reach consensus, the video was re-watched until consensus was reached.

LE Subtask Scoring

LE data for the single motor and dual task conditions were collected using iPod-based accelerometers that were attached to participants' ankles during the subtask. Gait performance data were collected by running the Sensor Data application (Wavefront Labs). Data from the right and left legs were wirelessly transferred to a computer and merged into one time-aligned Spike 2 (Cambridge Electronic Design Limited) data file for analysis by a trained research assistant to calculate secondary outcome measures. For the LE single cognitive and dual task conditions, videotape recordings were watched to determine the total number of words that the participant was able to produce during the allotted time. Repeated words were not counted.

UE Subtask Scoring

For the UE single motor and dual task conditions, video recordings were watched to determine the number of successful catches. A successful catch was counted if the participant threw the ball underhanded and caught it with their other hand (either overhand or underhand). If the ball hit the ground, this was not counted as a catch, but if the ball bounced off the participant's arm or trunk and was subsequently secured in his/her hand, this counted as a successful catch. For the UE single cognitive and dual task conditions, videotape recordings were watched to determine the total number of correct subtractions. If a participant made a subtraction error but then correctly subtracted 7, only one error was counted (e.g. 150, 144, 137 would count as one error and one correct subtraction).

4.2.5 Statistical Analysis

Our research objectives are twofold: establish if the revised DTS is sensitive to 1) dual task *motor* costs, and 2) dual task *cognitive* costs. Descriptive statistics were be used to summarize group data for the single and dual tasks. To determine if the revised DTS is sensitive to dual task motor costs, we used a one-tailed paired t-test to compare single and dual *motor* performance for the LE and UE subtasks. A one-tailed test was chosen as we hypothesized that participants would have worse performance under dual task conditions when compared to single task conditions. Additionally, we calculated a dual task motor effect (dual task performance/single task performance times 100) for each participant to evaluate the percentage of athletes who had a dual task motor cost on the LE or UE subtask. For the motor outcome measures of gait speed, step length, and total number of catches, if a dual task effect was greater than 100%, the participant had better performance during dual task conditions. Conversely, if a dual task effect was less than 100% for these outcome measures, the participant had poorer performance during dual task conditions. For the secondary LE motor outcome measures of total number of steps, step duration, and step duration variability, if a dual task effect was less than 100%, the participant had better performance during dual task conditions. Conversely, if a dual task effect was greater than 100% for these outcome measures, the participants had poorer performance during dual task conditions. To determine if the revised DTS is sensitive to dual task cognitive costs, we also used a one-tailed paired t-test to compare single and dual *cognitive* performance for the LE and UE subtasks. We also calculated a dual task cognitive effect for each participant to evaluate the percentage of athletes who had a dual task cognitive cost on the LE or UE subtask. Statistical significance for all one-tailed paired t-tests was set at $p < 0.0125$ (0.5/4) to account for multiple comparisons. Finally, each participant's dual task effects from the LE and

UE subtasks was evaluated to determine if the participant had a dual task motor or cognitive cost on the revised DTS. A dual task cost on either the LE or UE motor tasks represented that the revised DTS elicited, or was sensitive to, dual task motor costs. Similarly, a dual task cost on either the LE or UE cognitive tasks represented that the revised DTS elicited, or was sensitive to, dual task cognitive performance. The percentage of participants who have a dual task motor cost was calculated for each subtask, as well as the percentage of participants who had a dual task cognitive cost for each subtask. Additionally, the percentage of participants who had a dual task motor cost on either or both the LE or UE subtask was calculated to determine the sensitivity of parallel administration, or administration of both the LE and UE subtask, of the DTS. Similarly, the percentage of participants who had a dual task cognitive cost on either or both the LE or UE subtask was calculated to determine the sensitivity of parallel administration of the DTS.

4.3 Results

4.3.1 Dual Task Motor Costs

Our first research objective was to demonstrate that the revised DTS is sensitive to dual task motor costs in healthy, young adult female athletes. Statistically significant differences were observed between single-condition and dual-condition motor performance on both the LE and UE subtasks. In the LE subtask, participants walked significantly slower during the dual task condition (M = 1.50 m/s, SD = 0.26) than the single task condition (M = 1.73 m/s, SD = 0.23), $t(18) = 6.033$, $p < 0.001$, $d = 1.385$ (Figure 1A). Additionally, statistically significant differences were observed for all secondary motor outcome measures from the LE subtask (Table 1). In the UE subtask, participants had significantly fewer catches during the dual task condition (M = 15.16, SD = 3.86) than the single task condition (M = 18.84, SD = 4.26), $t(18) = 3.600$, p = 0.001, $d = 0.826$ (Figure 1B).

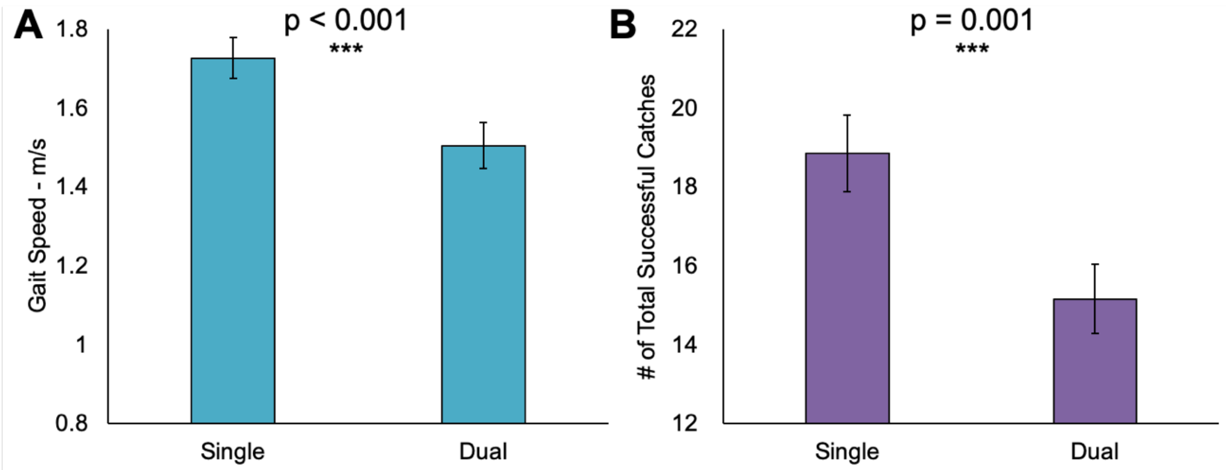

Figure 4.1. Single versus dual condition performance: primary motor outcome measures. Both the Lower Extremity (A) and Upper Extremity (B) subtasks elicited poorer dual-condition motor performance; significant differences in performance were observed between single and dual task conditions. Error bars represent the standard error. Asteriks (*) represent the significance level; *** represents a p-value < 0.001.

Table 4.2

Secondary Outcome Measures: LE Motor Task (Obstacle Walk)

Secondary Outcome Measure	Single		Dual				
	Mean	Std. Deviation	Mean	Std. Deviation	*p*	*t*	*d*
Number of Total Steps	22.84	2.14	24.32	2.19	< 0.001	-4.379	1.008
Average Step Length (m)	0.79	0.07	0.75	0.07	< 0.001	4.248	0.973
Average Step Duration (s)	0.49	0.05	0.52	0.05	< 0.001	-4.289	0.985
Step Duration Variability	0.08	0.07	0.11	0.10	0.002	-3.268	0.752

A dual task effect (dual task performance/single task performance) was calculated to determine the percentage of athletes who had a dual task motor cost on the LE and UE subtasks (Figures 2 and 3). When analyzing the primary LE motor task outcome measure only (gait speed), the LE motor task elicited a dual task cost in 84% of participants. Three participants, or

16%, walked faster (M = 0.04 m/s) during the dual task condition when compared with the single task condition. The dual task effect for the LE motor task primary outcome measure ranged from 72.5% (minimum) to 105.9% (maximum). When analyzing the secondary LE motor task outcome measures, the LE motor task elicited a dual task cost in 74% of participants for two of the outcome measures: number of total steps and step length. For the secondary outcome measure of step duration, the LE motor task elicited a dual task cost in 84% of participants. When analyzing step duration variability, the LE motor task elicited a dual task cost in 95% of participants. The UE motor task elicited a dual task cost in 68% of participants. Four participants, or 21%, had 1-4 more catches (M = 2.25) during the dual task condition when compared to the single task condition, while two participants, or 10%, had the same number of catches on both task conditions. The dual task effect for the UE motor subtask ranged from 47.8% (minimum) to 133.3% (maximum). Parallel administration of the LE and UE motor tasks rendered 95% sensitivity in detecting poorer dual task motor performance. In other words, 95% of participants had a dual task cost on either the LE or UE motor tasks.

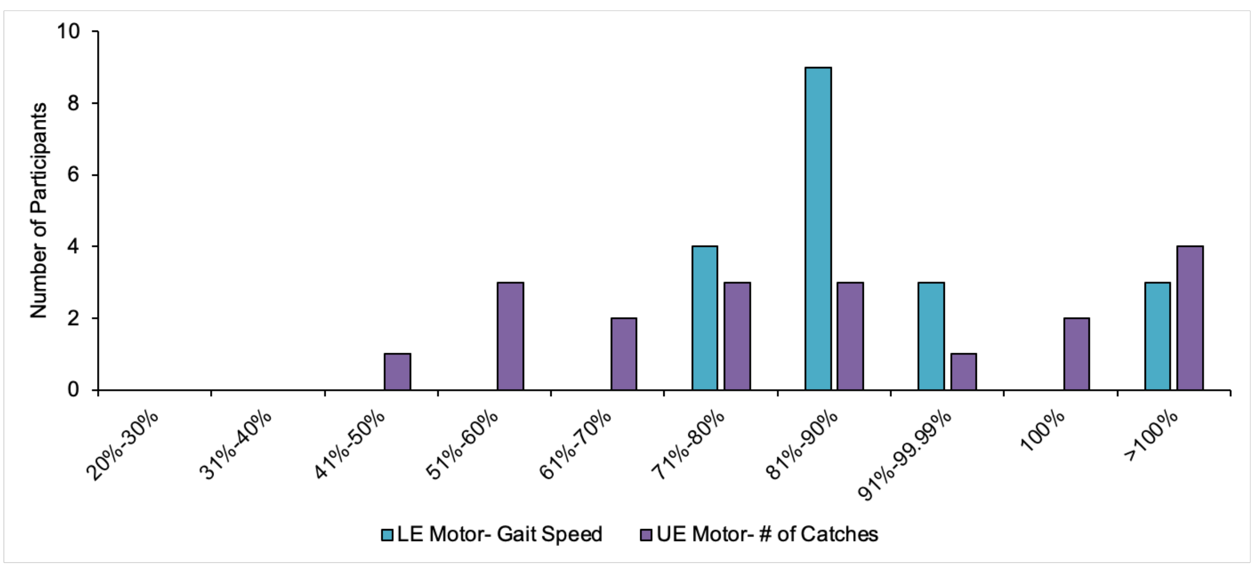

Figure 4.2. Dual task motor effects: primary outcome measures. The range of dual task motor effects (dual task motor performance/single task motor performance, represented as a

percentage) for the Lower Extremity and Upper Extremity subtasks. Parallel administration of both subtasks rendered 95% sensitivity in detecting poorer dual task motor performance.

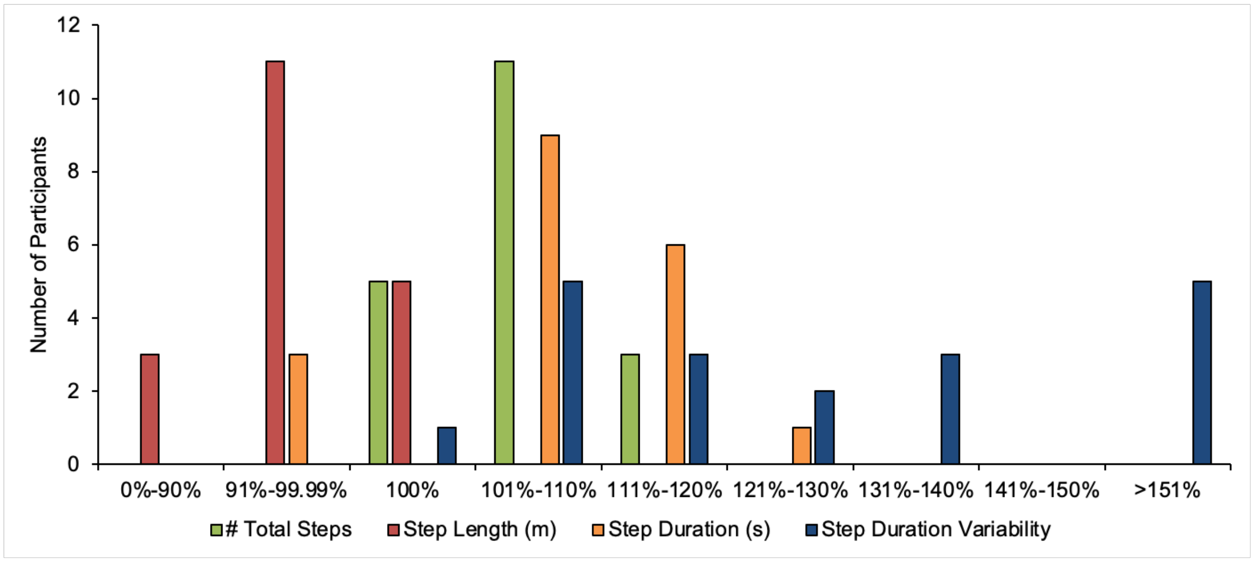

Figure 4.3. Dual task motor effects: secondary LE motor outcome measures. The range of dual task motor effects (dual task motor performance/single task motor performance, represented as a percentage) for the Lower Extremity secondary motor outcome measures. For # total steps, step duration, and step duration variability, a dual task effect greater than 100% represents poorer performance during the dual task compared to the single task.

4.3.2 Dual Task Cognitive Costs

Our second research objective was to demonstrate that the revised DTS is sensitive to dual task cognitive costs in healthy, young adult female athletes. While numerical differences were observed in the expected direction between single- and dual-condition cognitive performance on the LE subtask, these differences failed to meet the test-wise criteria for significance (p = 0.0125). In the LE subtask, participants produced fewer words during the dual task condition (M = 5.53, SD = 2.01) than the single task condition (M = 6.58, SD = 1.95), $t(18)$ = 2.416, p = 0.0135, d = 0.554 (Figure 4A). However, statistically significant differences were observed between single-condition and dual-condition cognitive performance for the UE subtask. In the UE subtask, participants had significantly fewer correct subtractions (M = 5.84, SD = 3.78) than the single task condition (M = 7.11, SD = 3.96), $t(18)$ = 2.554, p = 0.01, d = 0.585 (Figure 4B).

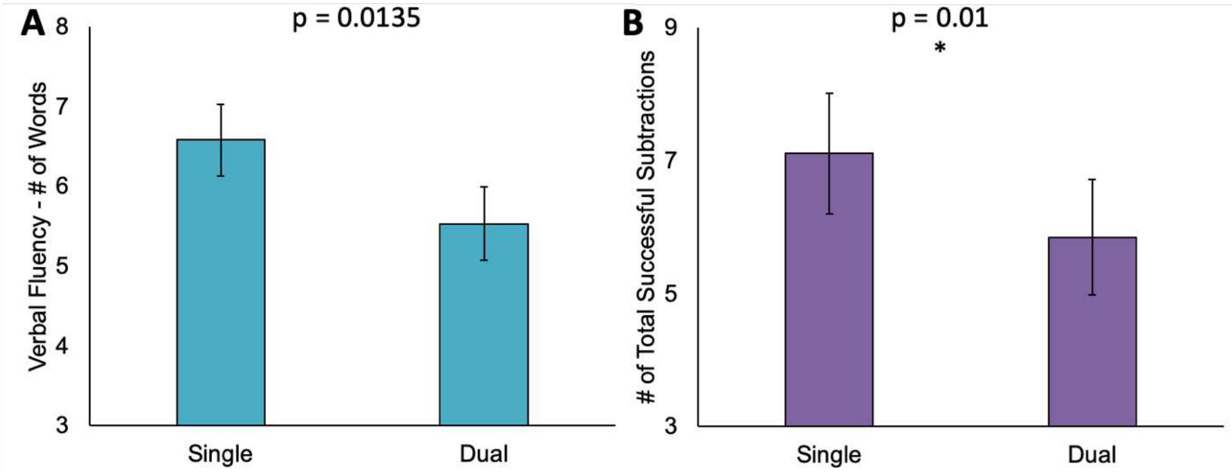

Figure 4.4. Single versus dual condition performance: cognitive outcome measures. Both the Lower Extremity (A) and Upper Extremity (B) subtasks elicited poorer dual-condition cognitive performance. Numerical differences in performance were observed between the Lower Extremity single and dual task conditions; significant differences in performance were observed between the Upper Extremity single and dual task conditions. Error bars represent the standard error. Asteriks (*) represent the significance level; * represents a p-value = 0.01.

A dual task effect (dual task performance/single task performance) was calculated to determine the percentage of athletes who had a dual task cognitive cost on the LE and UE subtasks (Figure 5). The LE cognitive task elicited a dual task cost (poorer dual task performance compared to single task performance) in 63% of participants. Four participants, or 21%, produced 1-2 more words during the dual task condition (M = 1.25) than the single task condition, while three participants, or 15%, produced the same number of words during both task conditions. The dual task effect for the LE cognitive task ranged from 38% (minimum) to 167% (maximum). The UE cognitive task elicited a dual task cost in 68% of participants. Six participants, or 32%, were able to correctly subtract 1-2 more numbers (M = 1.33) during the dual task condition compared to the single task condition. The dual task effect for the UE cognitive task ranged from 20% (minimum) to 300% (maximum). Parallel administration of the

LE and UE cognitive tasks rendered 84% sensitivity in detecting poorer dual task cognitive performance. In other words, 84% of participants had a dual task cost on either the LE or UE motor tasks.

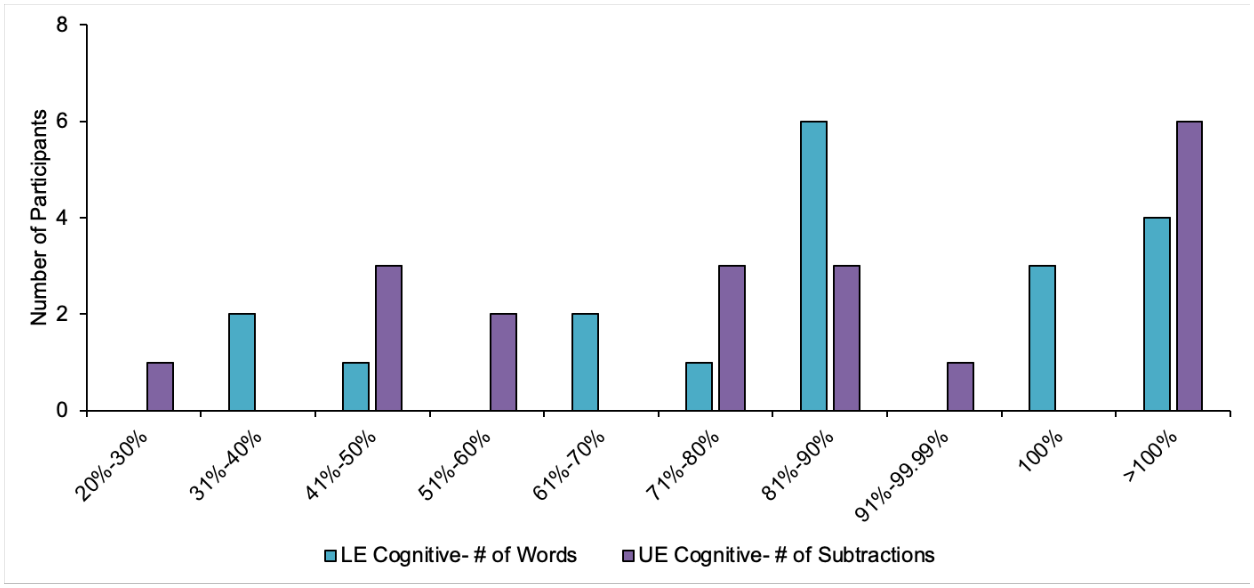

Figure 4.5. Dual task cognitive effects. The range of dual task cognitive effects (dual task cognitive performance/single task cognitive performance, represented as a percentage) for the Lower Extremity and Upper Extremity subtasks. Parallel administration of both subtasks rendered 84% sensitivity in detecting poorer dual task cognitive performance.

4.4 Discussion

This study had two main research objectives: 1) replicate pilot study findings and demonstrate that the revised DTS is sensitive to dual task motor costs in healthy, young adult, female athletes, 2) determine if the revised DTS is sensitive to dual task cognitive costs in healthy, young adult, female athletes. This study addressed many of the limitations found in the pilot study of the original DTS, such as the inability to evaluate dual task cognitive costs and the lack of precision germane to using manual stopwatches (Stephens et al., 2018). Additionally, we were able to replicate the results from the pilot study with an older cohort of healthy, young adult athletes. We were able to test 19 participants and established that the revised DTS could be administered with each participant in fewer than 10 minutes, even with the addition of a single cognitive trial and the use of smart devices for the LE trials. Importantly, the addition of smart devices allowed us to gather more precise and sensitive gait data without substantial increases in cost or time of administration when compared to the original DTS. This makes the revised DTS a viable screening measure for clinical use, as it is time efficient, low cost, and portable.

As in our previous work (Stephens et al., 2018), we observed significant dual task motor costs (i.e. significantly poorer performance on dual trials compared to single trials) on both the LE and UE subtasks for all outcome measures. The use of iPod-based accelerometers during the LE subtask allowed us to collect and analyze gait data that was not collected during the pilot study. We also found that the revised DTS was able to elicit a dual task motor cost in the majority of participants, although a few participants failed to demonstrate poorer dual task motor performance.

We found that the revised DTS elicited numerical dual task cognitive costs (i.e. poorer cognitive performance on the dual trials compared to the single trials) on both the LE and UE subtask, but only the UE subtask elicited performance differences that were statistically significant. Similar to the dual task motor effect, we also found that the revised DTS was able to elicit a dual task cognitive cost in the majority of participants. However, these results suggest that cognitive performance – as we measured it - was less susceptible to dual task interference than motor performance. This might be due to greater variability in cognitive task performance, as compared to motor task performance, particularly since we evaluated gait speed which is known to be consistent (Middleton et al., 2015). Alternatively, cognitive tasks may be more disruptive to motor performance than motor tasks are to cognitive performance. Finally, it is possible that most participants chose to prioritize cognitive performance over motor performance, thereby rendering more consistent cognitive performance between single and dual conditions with much poorer motor performance. These potential explanations should be tested with future research studies, which can use multiple trials or testing sessions to evaluate the consistency of dual task motor and cognitive costs.

The findings from this study align with current research surrounding the use of dual task paradigms in SRC management. Research using dual task paradigms has shown that dual tasks can elicit poorer dual task motor performance in adolescent and young adult athletes (e.g. Howell et al., 2017a; Büttner et al., 2020). Importantly, many of these studies do not include cognitive outcome variables, and instead focus on motor outcomes. Our results demonstrate that future dual task studies may benefit from inclusion of potential dual task cognitive costs to better understand their influence on dual tasks and potential for use with SRC management. Additionally, most research on dual task paradigms has focused on lower body or lower extremity motor skills; our study adds to the growing body of research by including a subtask that involves upper extremity motor skills.

4.5 Limitations & Future Directions

There are some limitations of the current study. While most of the participants in this study exhibited a dual task cost, or poorer dual task motor or cognitive performance, some participants had better dual task performance when compared to single task performance. These results may be due to the complexity of the motor and cognitive tasks included in the revised DTS, as motor and cognitive abilities may be influenced by the difficulty of the task. Prior research has shown that the complexity of the cognitive task used during a dual task can influence motor performance (Howell et al., 2014; Patel et al., 2014). Patel et al. (2014) found that verbal fluency and serial subtraction tasks elicited similar dual task motor costs, which may suggest that these tasks require similar cognitive demands to complete. Verbal fluency tasks require an individual to use semantic memory, while serial subtraction tasks challenge working memory. More complex cognitive tasks, such as a visual Stroop task, may involve executive function and information processing speed, which require a higher cognitive demand (Patel et al., 2014). Future iterations of the DTS can consider using tasks of greater complexity to attempt to elicit a dual task cost across all participants.

Another limitation of the current study was the number of trials included in the revised DTS. Participants completed the revised DTS in a particular trial order (single motor trial, single cognitive trial, dual task trial); thus, practice effects could have influenced a participant's motor and cognitive performance. This potential practice effect may be mitigated by having participants perform multiple trials of each trial type in a random order, which could result in more consistency in eliciting dual task costs.

Finally, the small, homogenous sample included in this study limits the generalizability of the findings. Further data collection from athletes across age, sex, sports, and competition level can improve our understanding of the sensitivity of the DTS. Future research with the DTS will also include athletes with sports-related concussion to test the specificity of the DTS to concussion-induced deficits. Additionally, a neuroimaging compatible version of the DTS has been created to understand the neural underpinnings of the motor and cognitive data collected while a participant is performing a single task compared to a dual task. The neuroimaging compatible version of the DTS also includes multiple trials of each trial type (single motor, single cognitive, and dual motor/cognitive) which may, as noted earlier, reduce or eliminate practice effects elicited by the revised DTS.

4.6 Implications for Occupational Therapy Practice

The findings of this study have the following implications for occupational therapy practice:

- Occupational Therapists (OTs) can provide distinct value by bringing a holistic, occupation-focused lens to SRC management. Having a comprehensive understanding of SRC sequelae can help to inform OT intervention and evaluation in athletes with SRC. By using assessments that are able to detect subtle behavioral or neurological deficits, OTs can better target interventions and evaluation strategies to ensure that they address these factors.
- SRCs can result in residual or subtle deficits that may not be found using traditional concussion assessments. Dual task assessments represent occupationally-based measures, as they attempt to mimic the occupational demands of playing a sport (i.e. simultaneous motor and cognitive tasks). Dual task assessments may be useful in making safer return-to-play decisions, ensuring an athlete's safety not only in their chosen sport, but across other meaningful occupations.
- Athletes represent a model population to study brain injury, as they are an accessible population for understanding this injury.

4.7 Conclusion

Dual task paradigms, such as the revised DTS, could potentially address limitations of SRC management, particularly insufficient difficulty of currently-used measures. Dual task paradigms may be able to help clinicians and providers involved in SRC management make safer return-to-play decisions, which is crucial to the health of athletes of all ages. The results from our study indicate that the revised DTS is a promising measure for use in SRC management and has been demonstrated to be sensitive to dual task motor and cognitive costs in healthy young adult female athletes. Future research will focus on the use of multiple trials to better understand potential practice effects, as well as the complexity of cognitive and motor tasks included in the DTS. Additionally, a neuroimaging-compatible version of the DTS will allow us to examine the neural underpinnings of the behavioral data collected using the DTS. Future studies with the DTS will help us to develop a clinically valid measure that can be used with athletes after SRC.

CHAPTER 5: PERSONAL REFLECTIONS AND CONCLUSIONS

As I reflect on my participation in Colorado State University's master's of occupational therapy program, I believe that my thesis project has provided me with invaluable learning opportunities that have supplemented my coursework. My thesis project has given me a deep appreciation for research and evidence-based practice. Additionally, completing this project during a global pandemic has made me become more flexible and creative. I am grateful to Dr. Stephens and Colorado State University as a whole for allowing me to continue to be a part of a research lab and complete my research project. Through this project, I have practiced skills that I hope to carry into my clinical practice, including how to analyze data, be a collaborative team member, and appreciate the importance of life-long learning.

My thesis project has made me appreciate the potential impact that OTs can make when working with athletes. This project has inspired me to consider how practitioners can enable athletes to not only perform in their meaningful occupation of sports, but also in other facets of their daily life. I believe that OTs can support athletes to enhance their occupational balance, performance, and participation. As I reflect on the knowledge that I have gained from completing my thesis on athletes with sports-related concussion, I hope to use this knowledge in my future practice as an occupational therapist who works with individuals who have had a brain injury. In my practice, I hope to advocate for the use of proactive care practices that use occupationally-focused, holistic, and sensitive evaluations to ensure the safety of athletes.

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