THE EFFECT OF MUSCLE FATIGUE ON SINGLE- AND DUAL-TASK WALKING AND OBSTACLE-CROSSING IN YOUNG ADULTS

by

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A THESIS

Presented to the Department of Biology
and the Robert D. Clark Honors College
in partial fulfillment of the requirements for the degree of
Bachelor of Science

June 2017

An Abstract of the Thesis of

Jocelyn Taylor for the degree of Bachelor of Science
in the Department of Biology to be taken June 2017

Title: The Effect of Muscle Fatigue on Single- and Dual-Task Walking and Obstacle-Crossing in Young Adults

Approved: _____

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Previous research has demonstrated independent effects of fatigue or concurrent cognitive task on walking and obstacle-crossing; however, limited studies were performed to examine their combined effects and interaction. The purpose of this study was to examine changes in gait characteristics and working memory performance of healthy young adults when lower extremity muscles are fatigued, during single- and dual-task walking/obstacle-crossing.

Twenty-four healthy adults (11 females, 20.7±1.3 years) were recruited for the study and performed the following five tasks immediately before and after a muscle fatigue protocol in randomized order: 1) performing an N-back test, 2) walking, 3) walking while performing an N-back test, 4) obstacle-crossing (OC), and 5) obstacle-crossing while performing an N-back test. Whole body motion data were collected from a set of twenty-nine retro-reflective markers with a 10-camera motion system.

Main effects: **Fatigue** increased *walking* step width, *obstacle-crossing* gait velocity, and caused closer placement of leading foot to obstacle. **Dual-task** *walking* decreased gait velocity, peak forward velocity, and stride length. **Dual-task** *obstacle-*

crossing decreased gait velocity, caused closer placement of leading foot to obstacle, and increased leading and trailing foot obstacle clearance.

Interaction effects: When **fatigued**, **dual-task** decreased *obstacle-crossing* peak forward velocity and *walking and obstacle-crossing* N-back accuracy. When **pre-fatigue**, **dual-task** increased *walking* N-back accuracy but decreased *obstacle-crossing* N-back accuracy. During **single-task**, **post-fatigue** increased *obstacle-crossing* peak forward velocity and *walking and obstacle-crossing* N-back accuracy. During **dual-task**, **post-fatigue** decreased *walking* N-back accuracy.

Our research supports the conclusion lower limb muscle fatigue under single- and dual-task walking and obstacle-crossing significantly affects gait characteristics and working memory performance.

Acknowledgements

I would like to thank Dr. Li-Shan Chou, Dr. Barbara Mossberg, and Szu-Hua "Teresa" Chen for being my guides on this dynamic journey. Your excellent mentorship has given me knowledge, confidence, and panache, all of which I will take into the future and live by faithfully. I want to extend a special thank you to Teresa; Teresa was my number one point person, and, even better, put up with my quirky personality for two years. Finally, I want to thank my family and friends for their love and support throughout the entire process.

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Introduction and Background

Muscle fatigue is a common problem that limits not only motor but cognitive performance. Both the inaccuracy of movement and executive dysfunction increase risk of falling accidents and raise the probability of injuries, especially when encountering a balance threatening situation like obstacle-crossing. Although there is little research examining the effects of muscle fatigue on muscle activity and walking characteristics, as well as a few on cognitive performances during obstacle-crossing, none of these studies have considered both aspects simultaneously. However, daily living performance necessitates both adequate motor control and cognitive function.

Walking while performing a cognitive task may occur concurrently with muscle fatigue, especially towards the end of active jobs. Muscle fatigue, referring to a reduction of force-generating capacity or inability to maintain the required level of strength during exercise (Edwards, 1981), is a common complaint among people; however, muscle fatigue critically impacts human motion in subtle ways which may increase the potential of significant accident during daily activities such as walking and obstacle-crossing.

For those prone to fatigue, such as older adults or labor-intensive workers, the effects of muscle fatigue on gait characteristics need to be even more urgently investigated in order to aid health professionals in designing proactive program which educate these at-risk populations. Through this, injuries due to falling can be prevented, high medical-associated costs could be reduced, and the health care system would be freed up. According to the 2014 Liberty Mutual Workplace Safety Index, falls on the same level ranked second of leading cause of all workplace injuries with direct costs of

$9.19 billion and accounted for 15.4 percent of the total workplace injury burden. In 2013, about 2.5 million people aged over 65 years were treated by medical services for fall-related injuries costing $43 billion (CDC and Prevention, 2015). Worse, this problem is growing year by year, establishing the urgency needed to effectively address it.

Fall prevention and interventions that promote safe walking after muscle fatigue can be facilitated by a better understanding of consequences from motor and cognitive performance and their interaction. An often utilized cognitive process is "working memory"; working memory describes a person's ability to temporarily process and store information (Gathercole et. al., 2014), thus working memory may support a range of critical everyday cognitive processes, including language comprehension and reasoning. The purpose of this research is to investigate how muscle fatigue affects gait characteristics and working memory performance during walking and obstacle-crossing. The knowledge gained from our proposed research will enhance our capability to 1) identify the impact of muscle fatigue on human gait characteristics which could be potential risk factors for falling accidents, and 2) to provide a baseline database for further research on fatigue-prone population.

Specific Aims

The purpose of this research was to investigate how muscle fatigue affects gait characteristics and working memory performance during walking and obstacle-crossing. The specific objectives include:

1) to compare the differences in **gait characteristics** during single-task (walking or obstacle-crossing) and dual-task (with concurrent working memory task) before and after muscle fatigue,

2) to compare the differences in **working memory performance** during single-task (sitting and responding to working memory test) and dual-task (walking or obstacle-crossing while simultaneously responding to working memory test) before and after muscle fatigue.

Literature Review

Walking has been shown to be altered with lower extremity fatigue (Abd-Elfattah et. al., 2015, Longpré et. al., 2013). Abd-Elfattah et. al., (2015) found muscle fatigue impacted not only muscle activity by decreasing electromyographic (EMG, force) production, but also impacted cognitive performance, interfering with executive function. In 2008, Parijat et. al. indicated localized quadriceps muscle fatigue affected various kinematic and kinetic gait variables that were linked with a higher risk of slip-induced falls. A systematic review by Beauchet et. al. (2009) showed significant changes in dual-task performance which were significantly associated with an increased risk of falling. Thus, both muscle and cognitive changes resulting from muscle fatigue could be potential risk factors for falls.

Researchers have demonstrated there is a tendency to decrease gait speed, stride length (Granacher et. al., 2010) and knee extension moment (Longpré et. al., 2015) in young adults during walking after muscle fatigue. In the elderly population, there is evidence of a reduction of single limb stance time, an increase of postural sway, step width and medio-lateral trunk accelerations during walking, and an impaired distance of

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functional reach and sit-to-stand repetitions after muscle fatigue (Helbostad et. al., 2010). The dissimilarity of findings between young and elderly population may be due to these populations' intrinsic physiological states which naturally translate into different compensatory strategies in order to enhance stability and avoid a fall. However, it is important to note that in both elderly and young populations we see evidence that muscle fatigue dynamically changes gait characteristics.

The declined accuracy of movement and changed coordination of muscle activity that accompanies muscle fatigue may make obstacle-crossing more difficult and increase the risk of tripping, which is one of the most frequent causes of falls. The foot placement of the trailing foot (the foot crossing the obstacle last) is seen to significantly decrease with fatigue (Antonopoulou et. al., 2014), thus increasing the risk of unsuccessful foot clearance over an obstacle, especially in the absence of visual feedback. Furthermore, these researchers also noticed EMG activity of the medial gastrocnemius of the trailing leg increased during the crossing phase, indicating an increased antagonist co-activation in order to enhance the stability of limbs and body through space when crossing. Although it is known the attentional demands needed for dynamic stability should increase when encountering a difficult task like obstacle-crossing, few of the studies investigated simultaneous motor and cognitive activity for interaction effects. This is in our area of interest and we will investigate this in our research.

As for cognitive performance, there is no consistent result of its change after fatigue. Granacher et. al. in 2010 investigated the effects of localized muscle fatigue, induced by repetitive voluntary isometric contraction on a dynamometer, on gait

characteristics under single and dual-task conditions in younger and older adults. The results showed cognitive performances assessed by reciting out-loud serial subtractions by three following fatigue were improved in both groups. Another study which utilized the auditory Stroop test to examine executive function of the brain during obstacle-crossing observed no cognitive task difficulty (Worden et. al., 2015). On the other hand, participants of another study demonstrated significant disruption of short-term memory to memorize a string of digits after a two-hour run on a treadmill at 65% of maximal oxygen uptake (Cian et. al., 2001). For those performing a maximal treadmill exercise to maximal oxygen uptake, the verbal memory composite scores of immediate post-concussion assessment and cognitive testing (ImPACT) was noted as impaired, thus demonstrating decreased working memory performance and visual-motor response speed. It seems the choice of the secondary, cognitive task and the method of inducing fatigue may have influences on the study's outcome, making conclusions here concerning muscle fatigue's effects on cognitive performance hard to confirm.

In this study, the auditory N-back task and sit-to-stand fatigue protocol were adopted. An N-back task is a cognitive test employed to assess executive working memory, an aspect which has been shown to decline after muscle fatigue as described above. When examining the dual-task interference with obstacle-crossing, it is appropriate to choose an auditory working memory task as it does not engage the visual system, thus minimizing potential structural interference (using the same input or output system for two competing tasks which would overload the capacity of that system). The N-back task has also been suggested to have greater dual-task effects on walking gait than basic motor-verbal attending and responding (Walshe et. al., 2015). Since there is

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no reason to ask the participant to decide which leg is leading and trailing limb when walking or obstacle-crossing, a sit-to-stand fatigue protocol is used to induce muscle fatigue on both legs simultaneously. Previous studies which adopted fatigue protocol with the dynamometer can only fatigue the muscles of one side at a time, causing gait characteristics to potentially be uneven relative to both sides when assessing whole body movement.

In summary, muscle fatigue is a common problem that limits motor and potentially working memory performance as well. In addition, cognitive tasks may interfere and alter gait characteristics when performed simultaneously with motor functions. Both the inaccuracy of movement and potentially decreased executive function could lead to falling accidents and raise the probability of injuries, especially when encountering a balance-threatening situation like obstacle-crossing. Although previous research has demonstrated independent effects of fatigue and working memory tasks on walking, their interaction is rarely considered. However, optimization of daily living performance necessitates both adequate motor control and working memory function, at times simultaneously. In consideration of this, the aim of this research is to investigate the effects of lower limb muscle fatigue on human motion and working memory performance in healthy young adults, measured by gait characteristics of walking and obstacle-crossing as well as accuracy of the auditory N-back test, under single and dual-task condition.

Methods

Subject Pool

A total of twenty-four healthy young adults from the local community (primarily from the University of Oregon) were recruited for this study via word of mouth and flyers (Appendix A) The inclusion criteria for these subjects were 1) 18-40 years old, 2) able to walk over ground and cross over (single-step) an obstacle without an assistive device, and 3) have normal hearing. Subjects were excluded from the study if they had 1) a history of neurological disease or head trauma, 2) impairments involving bones, muscles, or joints in the past six months, 3) persistent symptoms of dizziness, lightheadedness, unsteadiness, or any other medical condition that may affect walking ability or ability to step over an obstacle, and 4) any extreme strenuous activity in the past 24 hours before the test.

Testing Protocol

Recruited subjects were instructed to visit the Motion Analysis Laboratory (B52 Gerlinger Annex) at the University of Oregon and commit to one session of experimentation that would last approximately two hours. Before the study, the experimental purposes and protocols were explained in detail and subjects were asked to give their written consent before participation (Appendix B) and fill out Part 2 of the "Habitual Physical Activity and Healthy History Questionnaire" (Appendix C). Basic and anthropometric data were then recorded, including age, body weight, height, ankle width, knee width, and height of foot, all of which was recorded on our data collection sheet (Appendix D).

Subjects then underwent a muscle strength test in order to determine baseline lower limb strength. Afterwards, reflective markers were placed on bony landmarks and head, the microphone headgear was placed, and subjects were allowed to practice the N-back test until being fully familiar with it. Subjects then performed the following tasks in a randomized order: 1) sitting while responding to the N-back test, 2) walking, 3) walking while responding to the N-back test, 4) obstacle- crossing, and 5) obstacle-crossing while responding to the N-back test. Each task took approximately 2-3 minutes to complete. During tasks when the N-back was performed simultaneously while walking or obstacle-crossing, the participants were instructed not to prioritize one over the other but to perform both tasks at the same time to their best ability.

A muscle fatigue protocol was then implemented. Immediately afterwards, the subject underwent a second muscle strength test to determine the effect of the fatigue protocol on the subject's lower limb strength relative to baseline. Whatever the change in strength, the study was continued.

The subject then completed a second round of the five major tasks described above. Any lab equipment, including reflective markers, head cap, borrowed lab clothes, tape, and the auditory headpiece, were then removed and a final muscle strength test was performed by the subject to determine the level of recovery from the fatigue protocol. Finally, the subject was given time to ask any questions and debrief their experience with the researchers. The tasks stated above are explained more thoroughly below.

Experimental Techniques

Walking task

The subject walked at a self-selected comfortable speed along an 8-meter walkway. This was performed a few times consecutively in order to gain an average of a subject's gait characteristics through collection of approximately 5-8 trials. A set-up the lab space including the walkway and activated cameras is shown in Figure 1.

Figure 1. The Motion Analysis Laboratory at the University of Oregon

Obstacle-crossing task

The subject walked toward an obstacle at a self-selected comfortable speed and stepped over it. This was performed a few times consecutively in order to gain an average of a subject's gait characteristics through collection of approximately 5-8 trials. The obstacle consisted of a PVC pipe crossbar (1/2 inches diameter, 1.3 meter long) set atop two adjustable uprights. The height of the obstacle was set at 1/10 of the subject's height. The pipe was set up to be easily displaced without tripping if the subject failed

to lift their foot cleanly over the obstacle. A reflective marker was placed at each end of the pipe so the location of the pipe could be collected by the motion analysis system.

Whole body motion data collection

A ten-camera motion analysis system (Motion Analysis Corp., Santa Rosa, CA) was used to collect 3-D marker trajectory data sampled at 60 Hz. Marker position data were filtered with a low-pass, fourth order Butterworth filter with a cutoff frequency of 8 Hz by a 12 bit A/D converter (National Instruments, Austin, TX, USA) and were processed with Cortex software (Motion Analysis Corp., Santa Rosa, CA, USA). A set of 29 reflective markers were adhered on bony landmarks of the subject (Figure 2).
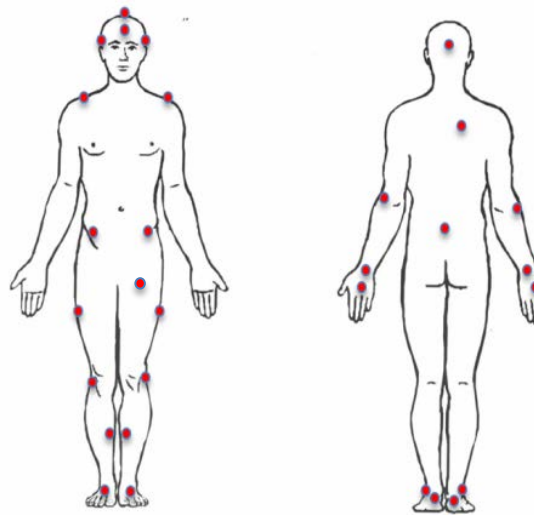
Figure 2. Marker Placement Diagram

An anatomical human diagram illustrating where reflective markers are positioned on the subject. This image was modified from: https://i.stack.imgur.com/wxVnc.jpg.

Fifteen markers were used to define the foot, leg, and thigh segments of both lower extremities. These markers were placed on the following anatomical landmarks: between the 2nd and 3rd dorsal metatarsals (toe markers), the posterior calcanei (heel

markers), the lateral malleoli (ankle markers), the lateral femoral epicondyles (knee markers), middle of the tibias (calf markers), lateral thighs (thigh markers), anterior superior iliac spines (ASIS) (pelvic markers), and the sacrum (low back marker). To define the arm segments, eight markers were placed on the top of the hands and wrists, lateral epicondyle of the humeri (elbow markers), and acromioclavicular joint of the shoulders (shoulder markers). To define the head, five markers were placed, with two just anterior (in front) to each ear, and one each on the front, back, and top of the head; a head cap was worn by subjects in order to provide a surface for the markers to be placed. One additional marker was placed on the right scapula (shoulder blade) for tracking purposes. Reflective markers were secured with double-sided adhesive tape rings as well as additional strips of tape. Due to the essential requirement for the ten-camera motion capture system to detect the reflective markers, tape was used to secure or modify any of the subject's clothing which might obscure the marker. This might include taping up a subject's shorts to decrease length and allow the cameras to capture the lateral thigh markers. This real-life set-up is illustrated in Figure 3.

Figure 3. Fully-Equipped Subject

A photograph of one of our subjects fully equipped per our study design.

N-back task

The auditory N-back task was designed to examine working memory, an essential component for attention, and was utilized in our research to assess executive function performance. The test consisted of a sequence of random numbers played from loudspeakers near the testing walkway. The subject was instructed to recognize the repetition of a number from N numbers ago. For example, if N = 2, and the number sequence was 1, 2, 1, the subject would have to answer "yes" or "match" when they heard the second "1" since the 1 was repeated from two numbers ago. N was determined during preliminary testing and familiarization of the test with the subject and depended on the subject's subjective self-assessment and testers' observations. Each N-back task took approximately 2 minutes to accomplish. The verbal responses from the subject were recorded from the microphone attached to a headpiece which the

subject wore during testing. Additionally, one researcher manually recorded the N-back test results (Appendix E). A schematic of the N-back test is shown in Figure 4.
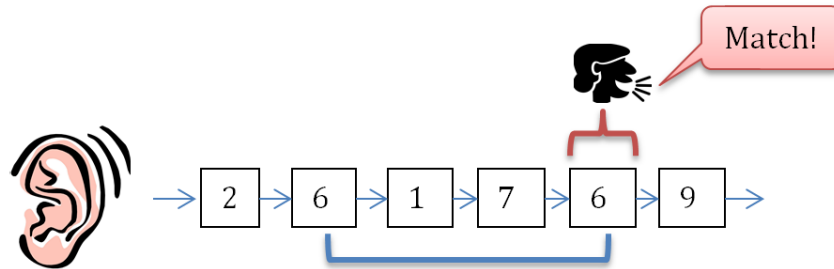
Figure 4. N-Back Test

This is a schematic of the N-back test, specifically the 3-back version. Parts of this schematic are supplemented with images from:
https://img.clipartfest.com/a55adae4a783d4bd1a344f0ffec676a1_ear-clip-art-clipart-ear-listening_954-1137.jpeg

Muscle strength test

The subjects were then positioned and restrained on a dynamometer (Biodex Medical Systems Inc., Shirley, NY, USA) at 60° of both the hip and knee joints with their right lateral epicondyle aligned to the axis rotation of dynamometer and right ankle fixed with the cuff placed 2 cm above the lateral malleolus (Figure 5). Prior to test, the participants were allowed to become accustomed to the dynamometer by performing brief submaximal isokinetic contractions of knee extension and flexion 2-3 times. During the maximum voluntary contraction (MVC) test, the participants were instructed to flex or extend the knee as hard as possible for 5 seconds during each movement, using the first few seconds to gradually but rapidly increase strength to maximal in order to avoid unnecessary excessive strain to the knee joint. There was a 5 second rest between each flexion and extension movement, and a 1 minute rest between each set of

flexion/extension, for a total of 3 sets. The highest value of torque output for both flexion and extension was considered the subject's baseline lower limb strength and was used for comparison to later MVCs in order to determine fatigue and recovery. Fatigue was defined as a reduction of 25% strength from MVC 1 (baseline) to MVC 2 (after fatigue protocol) as defined by Longpré et. al. (2013).

Figure 5. Muscle Strength Test

This photograph illustrates how a person sits in the dynamometer, ready to flex or extend their leg and provide lower limb strength data.

Fatigue protocol

A sit-to-stand task was adopted as a fatigue protocol. The participants sat on a chair without armrests and were instructed to do a repeated sit-to-stand movement at a pace of 0.5 Hz with arms crossed over the chest. The subject's head cap and auditory microphone were removed during this protocol. Part 1 of the "Habitual Physical Activity and Healthy History Questionnaire" (Appendix C) was completed simultaneously with the fatigue protocol, wherein a researcher asked the questions and

the subject's verbal response was manually recorded. A small fan was directed at the subject during the fatigue protocol. Subjects were offered a small bottle of water before this protocol and were given access to this water during the protocol as well, although subjects had to drink simultaneously while performing the protocol. The researchers verbally encouraged the participant to continue as long as possible. The fatigue protocol was stopped when 1) the participant indicated he or she was unable to continue, 2) the movement frequency fell below 0.5 Hz and continued to be low after encouragement, or 3) after 30 minutes. The instruction given to the participants was: stand up to an upright position with your knees fully extended, then sit back down and repeat this at the beat of the metronome until you can no longer perform the task. This protocol is illustrated below in Figure 6.
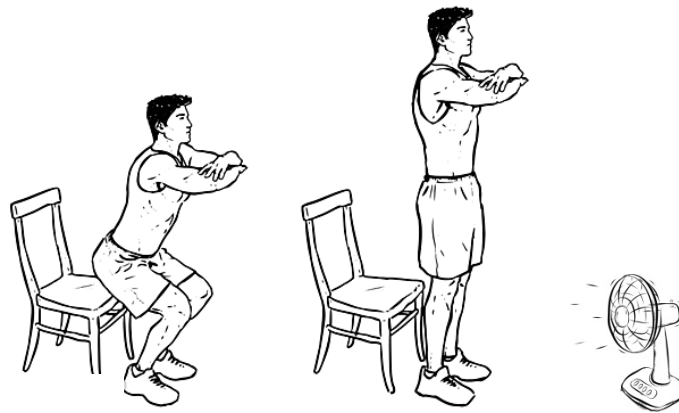
Figure 6. Sit-to-Stand Fatigue Protocol

This schematic illustrates how a subject completed the sit-to-stand fatigue protocol.
This image was modified from: http://workoutlabs.com/wp-content/uploads/watermarked/chair_squat.png.

Summary Timeline of Procedure

10 minutes – Complete consent form and questionnaire

05 minutes – Change/modify clothes (if necessary)

05 minutes – Anthropometric measurements

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05 minutes – Muscle strength test (MVC 1)

05 minutes – Reflective marker placements, auditory headpiece fitting

05 minutes – Practice N-back test

20 minutes – Complete the following tasks in a random order:

      (1) Sitting while responding to the N-back test,

      (2) Walking,

      (3) Walking while responding to the N-back test,

      (4) Obstacle-crossing,

      (5) Obstacle-crossing while responding to the N-back test

30 minutes – Fatigue protocol (time varies between subjects)

05 minutes – Muscle strength test (MVC 2)

20 minutes – Complete the following tasks in a random order:

      (1) Sitting while responding to the N-back task,

      (2) Walking,

      (3) Walking while responding to the N-back test,

      (4) Obstacle-crossing,

      (5) Obstacle-crossing while responding to the N-back test

05 minutes – Remove reflective markers, auditory headpiece

05 minutes – Muscle strength test (MVC 3)

Total estimated time: 2 hours

Data Analysis

Research Design

The study design was a prospective, randomized-order, and pretest/posttest design. It was a prospective study since the experimental procedure was executed after the participants were recruited. Five major tasks were completed by participants before and after fatigue protocol; the order of tasks was randomly decided, thus this research was a randomized-order study. The variables measured in this research were taken

before and after the fatigue protocol by the same researcher, thus it was a

pretest/posttest design.

Dependent variable analysis

　　This research focused on the changes in variables related to human gait as well

as working memory function, after a fatigue protocol was followed. Variables measured

during the experiments include gait velocity, peak forward velocity, stride length, stride

width, leading and trailing foot clearance height over an obstacle, leading and trailing

foot placement relative to obstacle when obstacle-crossing, and accuracy of working

memory test. All of these variables were collected before a subject was fatigued as well

as after they followed a fatigue protocol. Motion data including both kinetic and

kinematic data was first processed via Motion Analysis software (Figure 7, Cortex,

Motion Analysis Corporation) and then analyzed with custom-written Matlab.
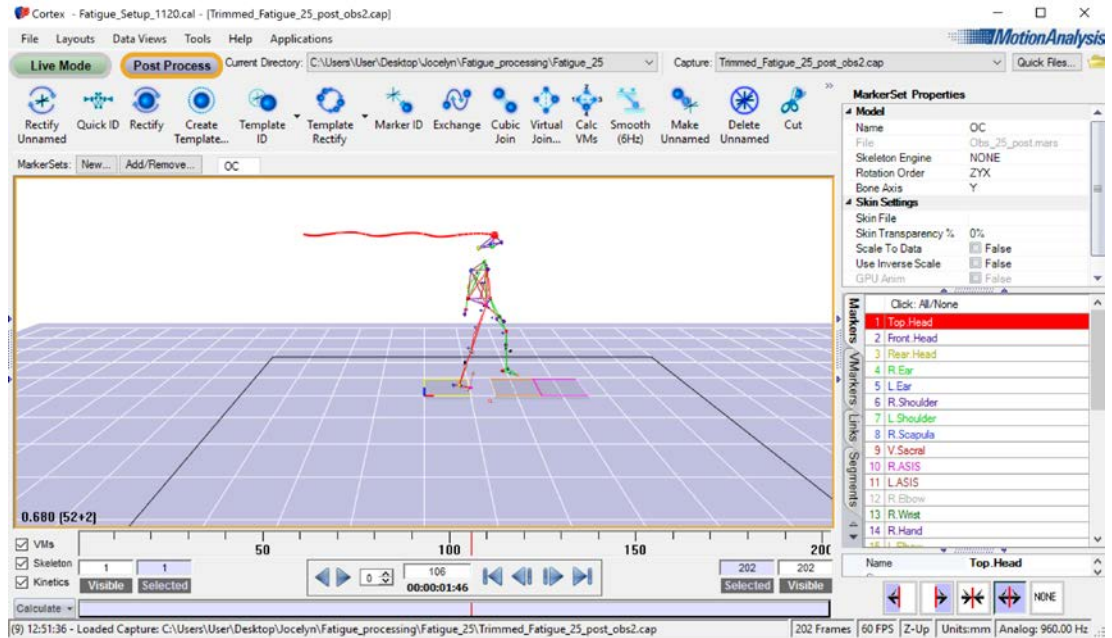
Figure 7. Processing Whole Body Motion Data Collection

This screenshot illustrates Cortex software processing raw data for further analysis. In this screenshot, a subject is in the process of stepping over the obstacle.

Leading and trailing foot clearance height was calculated as the vertical distance between a point in the middle of the obstacle and the toe marker placed between the 2nd and 3rd metatarsal when the toe marker was directly above the obstacle (Figure 8). The foot placement of leading foot was determined by the horizontal distances between the obstacle and the heel marker of the leading limb immediately after crossing the obstacle. The foot placement of the trailing foot was determined by the horizontal distances between the obstacle and toe marker of the trailing limb prior to crossing. Both of these variables are illustrated in Figure 9.
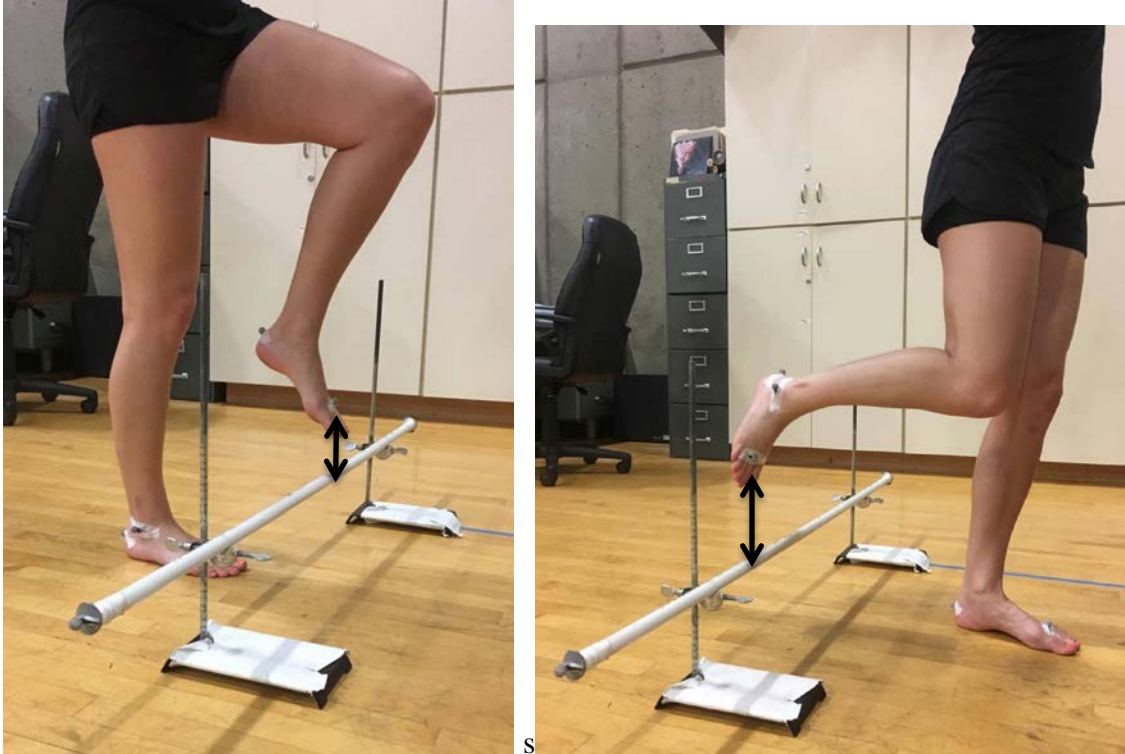
Figure 8. Leading and Trailing Foot Clearance Height

The arrows represent the leading (left) and trailing (right) foot clearance height when obstacle-crossing. Note only foot markers were placed on this model.

Figure 9. Leading and Trailing Foot Placement

The arrows represent the distance of leading (right) and trailing (left) foot placement when obstacle-crossing. Note only foot markers were placed on this model.

During obstacle-crossing trials, gait velocity was calculated as the mean forward velocity of the sacral marker during a crossing gait cycle, which was defined as the gait cycle starting with the heel strike of the trailing limb before the obstacle to the heel strike of the same trailing limb after the obstacle; stride length was the distance between these two heel strikes. For walking trials, stride length was calculated from the heel marker of the heel strike starting a gait cycle to the last heel strike. Stride width was the distance between the two markers on top of the feet.

The subject's accuracy performing the N-back test was determined by dividing the "number of missed correct match responses" by the "number of total digits" and

multiplying this quotient by 100%. If a subject signaled a match which was not a match, this false positive was treated as another missed correct match response.

Statistical analysis

All descriptive data were presented in mean ± SD. The data were first checked for normality with skewness, kurtosis, and the Shapiro-Wilk test. The critical value of the skewness and kurtosis for a normal distribution data were ranged from ± 1 and ± 2, respectively. If the p value of the S-W test was greater than .05, it indicated that the distribution of the data was normal. In contrast, if the p value of the data were less than .05, it was considered to have non-normal distribution. For the baseline comparison between the conditions, paired t-tests and Wilcoxon signed-ranks tests were used for the variables with normal distribution and non-normal distribution, respectively. A 2X2 analysis of variance (ANOVA) with repeated measures, using condition (walking or obstacle-crossing with and without concurrent working memory test; N-back only vs. N-back + walking or obstacle-crossing) and time (pre-fatigue and post-fatigue), was used to examine the condition and time effects for the parametric variables. The statistical significance level was set at $\alpha = 0.5$ while the power was set at $\beta = 0.8$. All the analyses were carried out using the software of Statistical Product and Service Solutions (SPSS) in its 23th version.

Results

Walking

Only 23 out of 24 subjects who participated in the study could be analyzed for walking due to technical difficulties in recording whole body motion data for one of the subjects (N = 23, 11 females). A table of the descriptive characteristics of these subjects is provided in Table 1.

Table 1. Descriptive Table of Subject Characteristics (Walking)

	Average	**Standard Deviation**
Age (years)	20.7	1.3
Height (cm)	171.1	6.8
Weight (kg)	68.6	9.5

This table provides some basic descriptive data of the subjects whose walking trials were properly recorded.

Gait Characteristics

For the purposes of this section, "single-task" will refer to a subject only walking, while "dual-task" describes when the subject walked while performing the memory test.

Gait velocity: Subjects walked more slowly during dual-task relative to single-task (1.17 ± 0.02 vs. 1.21 ± 0.02 m/sec, $p < .001$).

Peak forward velocity: Subjects exhibited lower peak forward velocity during dual-task relative to single-task (1.28 ± 0.03 vs. 1.34 ± 0.03 m/s, $p < .001$).

Stride length: Subjects exhibited decreased stride lengths during dual-task relative to single-task (1.17 ± 0.02 vs. 1.22 ± 0.03 m, $p < .001$).

Stride width: Stride width increased when subjects were post-fatigue relative to when they were pre-fatigue (8.7±0.4 vs. 7.8±0.4 cm, p = .005).

Working Memory

For the purposes of this section, "single-task" will refer to a subject performing only the working memory test, while "dual-task" describes when the subject walked while performing the memory test.

During single-task, the accuracy of the working memory test was greater post-fatigue relative to pre-fatigue (95.92 vs. 98.37%, p = .013), while during dual-task the accuracy was worse post-fatigue relative to pre-fatigue (97.44 vs. 94.09%, p < .001). During pre-fatigue, accuracy was greater during dual-task compared to single-task (95.92 vs. 97.44%, p < .001), while during post-fatigue the accuracy was greater during single-task compared to dual-task (98.37 vs. 94.09%, p < .001). All these results are illustrated in Figure 10.
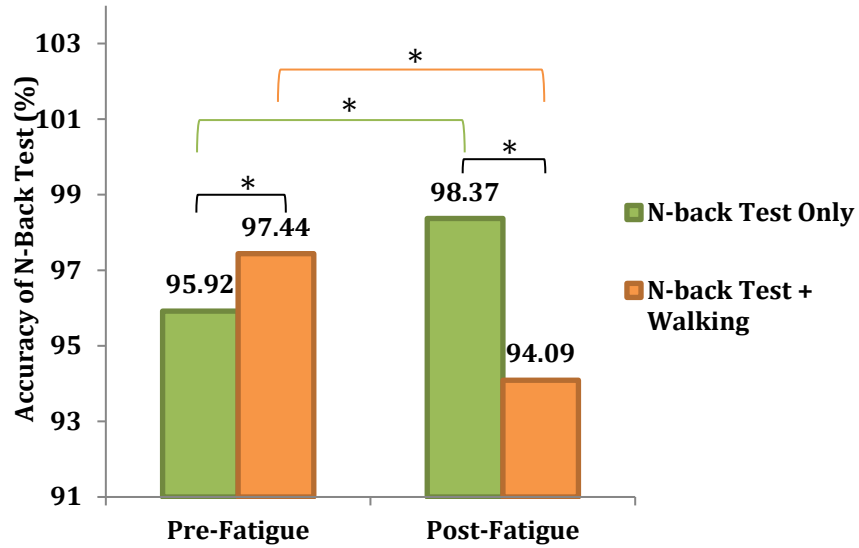
Figure 10. N-back Test Accuracy Pre- and Post-Fatigue across Conditions (N-Back Test or N-Back Test + Walking)

This graph illustrates the accuracy of the N-back test across conditions (single and dual-task), pre- and post-fatigue, $* p < 0.05$.

Obstacle-Crossing

Recordings for all 24 of the subjects tested were viable for analysis (N = 24, 11 females). A table of these subjects' descriptive characteristics is provided in Table 2.

Table 2. Descriptive Table of Subject Characteristics (Obstacle-Crossing)

	Average	**Standard Deviation**
Age (years)	21.1	1.3
Height (cm)	171.5	6.9
Weight (kg)	68.9	9.4

This table provides some basic descriptive data of the subjects whose obstacle-crossing trials were properly recorded.

Gait Characteristics

For the purposes of this section, "single-task" will refer to a subject only obstacle-crossing, while "dual-task" describes when the subject obstacle-crossed while performing the working memory test.

Gait velocity: Subjects exhibited greater average gait velocity post-fatigue than in pre-fatigue (1.038 vs. 1.074 m/s, p = 0.034). Subjects also exhibited greater average gait velocity during single-task compared to dual-task (1.083 vs. 1.029 m/s, p = 0.003).

Peak forward velocity: In the post-fatigue condition, subjects showed greater peak forward velocity during single-task than dual-task (1.34 vs. 1.28 m/s, p = 0.006). During single-task, subjects showed greater peak velocity during post-fatigue than pre-fatigue (1.29 vs 1.34 m/s, p = 0.012). These results are illustrated in Figure 11.
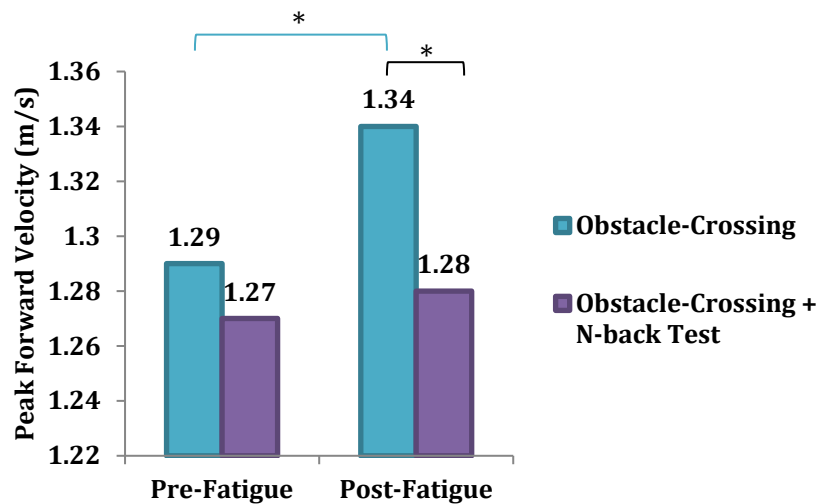
Figure 11. Peak Forward Velocity Pre- and Post-Fatigue across Conditions (Obstacle-Crossing or Obstacle-Crossing + N-back Test)

This graph illustrates the peak forward velocity across conditions (single and dual-task), pre- and post-fatigue, * p <0.05.

Foot placement (leading): Subjects placed their leading foot closer to the obstacle after crossing post-fatigue compared to pre-fatigue (20.99 vs. 22.37 cm,

p = 0.027). Subjects placed their foot closer to the obstacle after crossing during dual-task relative to single-task (20.66 vs. 22.70 cm, p < 0.001).

Foot clearance (leading): Subjects exhibited less clearance of their leading foot over the obstacle when performing single-task relative to dual-task (19.14 vs. 20.09 cm, p = 0.042).

Foot clearance (trailing): Subjects exhibited less clearance of their trailing foot over the obstacle when performing single-task relative to dual-task (15.60 vs. 16.63 cm, p < 0.001).

Working Memory

For the purposes of this section, "single-task" will refer to a subject performing only the working memory test, while "dual-task" describes when the subject obstacle-crossed while performing the working memory test.

N-back accuracy: During single-task, the accuracy of the working memory test was greater post-fatigue relative to pre-fatigue (98.44 vs. 95.93%, p <0.001). During pre-fatigue, accuracy was greater during single-task relative to dual-task (95.93 vs. 94.10%, p = 0.017), while during post-fatigue the accuracy was greater during single-task relative to dual-task (98.44 vs. 95.02%, p <0.001). All of these results are illustrated in Figure 12.
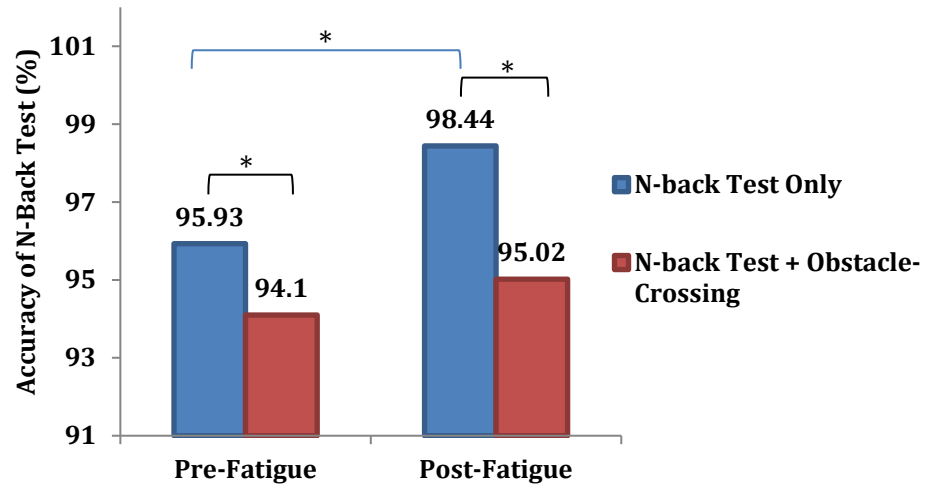
Figure 12. N-back Test Accuracy Pre- and Post-Fatigue across Conditions (N-back
Test or N-back Test + Obstacle-Crossing)

This graph illustrates the accuracy of the N-back test across conditions (single and dual-
task), pre- and post-fatigue, $p < 0.05$.

Discussion

The aim of this study was to determine how lower limb fatigue affected a person's walking, obstacle-crossing, and working memory ability. This study also analyzed our data for interaction effects between a combined task of walking and utilizing working memory as well as between obstacle-crossing and engaging working memory. This was primarily an exploratory study, so there were no hypotheses beyond our predication fatigue would cause some degree of change in walking, obstacle-crossing, and working memory ability.

We measured a variety of gait characteristics as well as accuracy of the working memory test. These variables were analyzed for main effects (significant difference between pre-fatigue and post-fatigue, or between single-task and dual-task) and simple effects (for example, significant difference between single-task and dual-task when fatigued).

Our study extracted a sizable amount of data from the experiment and found significant differences in a variety of variables between conditions. We found fatigue does affect gait characteristics. When fatigued, subjects significantly increased step width (walking trials), gait velocity (OC trials), and caused leading foot to be placed closer to the obstacle after crossing it (OC trials).

Adding a working memory test while simultaneously walking significantly changed some gait characteristics, including decreasing gait velocity, peak forward velocity, and stride length. We found adding a working memory test while simultaneously obstacle-crossing significantly changed some gait characteristics,

including decreasing gait velocity, placement of leading foot to be closer to the obstacle after crossing it, and more clearance of leading and trailing foot over the obstacle.

Interaction effects between fatigue and single- vs. dual-task resulted in some simple effects. When fatigued, subjects showed greater peak forward velocity (OC trials) and N-back test accuracy (walking and OC trials) during single-task relative to dual-task. Pre-fatigue, subjects' N-back test accuracy (walking trials) was greater during dual-task compared to single-task. However, pre-fatigue N-back test accuracy (OC trials) was greater during single-task relative to dual-task.

During single-task, subjects showed greater peak velocity (OC trials) and greater N-back test accuracy (walking and OC trials) post-fatigue relative to pre-fatigue. During dual-task, subjects had worse N-back test accuracy (walking trials) post-fatigue relative to pre-fatigue.

This discussion further analyzes our results, comparing them to current literature when applicable as well as postulating as to why any changes might have occurred. Each variable with significant changes due to any effect is further explained in the following sections.

Gait Velocity

Subjects decreased their gait velocity during **dual-task walking**, as compared to **single-task walking**. This is a reasonable result purely when considering the fundamental nature of engaging in higher thought processes such as working memory; when focused on an internal thinking task, it stands to reason there is less attention directed to the body, resulting in less driven movements. Indeed, Beauchet et. al. (2005)

found healthy young adults counting backwards while walking exhibited significant decreases in stride velocity.

Similarly, subjects decreased gait velocity during **dual-task obstacle-crossing**, as compared **single-task obstacle-crossing**. This agrees with the review *The role of executive function and attention in gait*, in which Galit et. al. (2007) finds healthy young adults adopt a more cautious, slower gait when mentally distracted. Furthermore, Gage et. al. (2003) finds "fall-related anxiety predicts an increase in the allocation of attention to locomotor control;" I suggest obstacle-crossing itself is cause for "fall-related anxiety" and further corroborates why gait velocity decreases in this condition; the subjects' anxiety for obstacle-crossing slows their speed.

However, subjects increased gait velocity when **fatigued obstacle-crossing** compared to **pre-fatigue obstacle-crossing**. This is a surprising finding as muscle fatigue decreases the ability of a person to efficiently recruit muscle fibers, thereby temporarily reducing strength and speed ability of the muscle (Roger et. al., 2008). Interestingly, we do not see this fatigue effect for gait velocity in walking trials, suggesting obstacle-crossing and walking uniquely contribute to gait velocity regulation when a person is fatigued. However, Barbieri and Santos et. al. (2013) found fatigued healthy young adults increased gait velocity both during walking and obstacle-crossing tasks, suggesting there is no unique effect between walking and obstacle-crossing and that our study somehow contributed to slower walking when fatigued.

This result may also be influenced by the learning effect between the first round of task (pre-fatigue) and the second round (post-fatigue). Subjects may have become accustomed to the equipment they wore (reflective markers, headgear, taped clothing,

etc.) by post-fatigue tasks and consequently walked and obstacle-crossed in a more comfortable, faster, manner.

Peak Forward Velocity

Subjects decreased their peak forward velocity during **dual-task walking** as compared to **single-task walking**. This result is similar to the above discussion on gait velocities, specifically how adding a concurrent working memory task during walking decreases a person's ability to regulate speed control. As attention is partitioned to the working memory test, locomotion becomes conserved and minimized.

Fatigued subjects exhibited lower peak forward velocities during **dual-task obstacle-crossing** compared to **single-task obstacle-crossing**. Once again working memory appears to adversely affect speed control; attention that might have originally been reserved for maintaining normal fatigued speeds is instead given to mental tasks. Furthermore, peak forward velocity can be indicative of gait balance control; peak forward velocity is found in the "lurch" of walking forward and may be influenced by the ability of a person to hold them stable while stepping through space. Indeed, Lockhart et. al. (2013) has found the push-off force of the stance leg is reduced after localized muscle fatigue of the quadriceps, so muscular fatigue may destabilize a person, causing a more pronounced "lurch" forward.

We do not see this simple effect in **fatigued** subjects during **single-task walking** relative to **dual-task walking**, so I propose obstacle-crossing redirects mental attention captured by the N-back test back towards locomotion (Gage et. al., 2003), slowing the force of the subject forward as they juggle a mental task with a more challenging and anxiety-producing physical task. Conversely, this result could be explained by the

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anticipation of crossing an obstacle, as this mental anticipation may combine with the already-slowing effects of the N-back test, further stealing attention from gait velocities and slowing a person down. Brown et. al. (2006) notes conservative gait patterns, including reduced gait speed, emerge in anticipation of encountering obstacles; therefore, there is a reasonable chance anticipatory mental process is why we only find this result in obstacle-crossing trials.

During **single-task obstacle-crossing**, subjects exhibited increased peak forward velocity **post-fatigue** relative to **pre-fatigue**. As peak forward velocity during obstacle-crossing likely occurs when swinging the foot and body forward over the obstacle, it is reasonable to suggest the added movement to clear the obstacle is further destabilizing; adding lower limb fatigue to this task could easily destabilize subjects to a greater degree and cause a more pronounced "tilt" forward on the step down, causing significant increased peak forward velocity. Finding of increased obstacle-crossing gait speeds in fatigued subjects corroborate this result (Barbieri and Santos et. al. (2013)).

Stride Length

Subjects decreased stride length during **dual-task walking** as compared to **single-task walking**. The effect of dual-task on stride length is consistent with those found in gait velocities; specifically, in how the nature of a working memory task limits normal gait characteristics. Thus, I continue to suggest the auditory N-back test assigned to our subjects reduces their normal thoughtfulness towards physical endeavors, reducing their ability to monitor and maintain various gait characteristics, including stride length.

Stride Width

Subjects in **single-task walking** increased stride width when **fatigued** compared to **pre-fatigue**. Barbieri and Santos et. al. (2013) also found that healthy young adults who were fatigued exhibited increased step width. If people become less stabilized when fatigued, they are likely going to attempt to stabilize themselves; Maki in 1997 suggested increased step width, among other changes to gait characteristics, were stabilizing adaptations in response to the fear of falling. Thus, I suggest our subjects subconsciously widened their steps to obtain larger foundational support for movement after fatigue in response to an increased risk of falling due to fatigue and muscle balance control.

Foot Placement (Leading)

Subjects placed their leading foot closer to the obstacle after crossing when **fatigued obstacle-crossing** compared to **pre-fatigue obstacle-crossing.** Again, I interpret fatigue as a de-stabilizer; in this case the fatigued subject compensated for their instability by stepping closer to the obstacle after crossing, thereby reducing the time and distance they must surmount to complete the crossing.

Subjects placed their leading foot closer to the obstacle after crossing during **dual-task obstacle-crossing** compared to **single-task obstacle-crossing.** Similar to previous effects between single and dual-task, the auditory N-back test seems to favorably redistribute attention toward mental from physical, manifesting in this case as a subject stepping closer to the obstacle after crossing; from this, the subject may be able to lend more attention to their working memory rather than toward the challenging task of obstacle-crossing, as less time and effort is devoted to crossing. Woollacott et.

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al. (2002) found healthy young adults engaging in cognitive tasks showed reduced stability during walking, further upholding how mental processes detract from physical awareness and ability so as to supplement cognitive tasks.

Foot Clearance (Leading)

Subjects exhibited more clearance over the obstacle with their leading foot during **dual-task obstacle-crossing** compared to **single-task obstacle-crossing**. This finding contributes to the idea that mental distraction results in physical carefulness; in this case, through overcompensation when clearing an obstacle. This idea that cognitive tasks result in overcompensation in physically challenging tasks is seen in a study by Doi et. al. (2011) which found people on the phone (distracted mentally) turned their trunk at greater degrees when maneuvering through a doorway.

Foot Clearance (Trailing)

Similar to leading foot clearance over an obstacle, subjects exhibited more clearance over the obstacle with their trailing foot during **dual-task obstacle-crossing** compared to **single-task obstacle-crossing**. Attention fundamentally has a capacity (Kim et. al., 2007) and must be portioned effectively in order to carry out daily activities; when a dual-task occurs, attention is divided according to difficulty of the task or priority of one over the other. Because all subjects were instructed to not prioritize one task over the other in dual-task, it was the difficulty of the task which captured the most attention and harmed the other concurrent task more acutely. Again, I suggest the addition of a mental task cues physical overcompensation when maneuvering through a challenging task.

N-back Accuracy

　　Fatigued subjects exhibited worse N-back test accuracy during **dual-task walking** compared to **single-task N-back.** Moreover, **fatigued** subjects exhibited worse N-back test accuracy during **dual-task obstacle-crossing** compared to **single-task N-back.** A combination of fatigue and engaging in a working memory test significantly decreases the ability of subjects to accurately answer the N-back test. This finding suggests muscular fatigue during locomotion further detracts from a person's ability to concentrate on mental tasks. Srygley et. al. in 2009 concluded gait is more attention-demanding than previously thought, even in healthy young adults, through his findings that difficult cognitive tasks suffer in the context of walking. Fatigue has been shown to increase the difficulty of motor control through destabilizing effects (Barbieri and Lee et. al., 2013), causing prioritization towards locomotion; furthermore, Woollacott et. al. (2002) found healthy young adults demonstrated reduced walking stability when dual-tasking, adding to the instability a fatigued dual-tasking subject experiences. This combination of fatigue and dual-task might have made walking and obstacle-crossing so challenging the N-back test suffered due to reprioritization of attention towards the physical over the mental.

　　Similarity, subjects during **dual-task walking** exhibited worse N-back test accuracy during **post-fatigue** compared to **pre-fatigue.** Again the effect of fatigue appears to redirect attention to the physical component of dual-tasking, reducing working memory performance.

　　Interestingly, subjects during **single-task N-back** exhibited greater N-back test accuracy during **post-fatigue** compared to **pre-fatigue.** Similar findings by Granacher

et. al. (2010) showed fatigue in both older and younger adult populations improved cognitive performance. It is important to consider exercise's ability to "warm-up" a subject; because our subjects could stop the fatigue protocol at any point, they may not have maximally exhausted muscular capabilities. In these cases, the fatigue protocol might have only aroused them and altered cognitive processes. Kamijo et. al. in 2009 concluded light and moderate aerobic exercise improved cognitive function in healthy young and old adults. This might explain why N-back test accuracy improved when subjects were fatigued.

This result may also be influenced by the learning effect between the first round (pre-fatigue) and the second round (post-fatigue) of tasks. Subjects may have become accustomed to the nature of the N-back test (a working memory test people typically do not have practice in) by the post-fatigue tasks and consequently were able to detect matches more accurately by simply learning how to more effectively process it.

Pre-fatigued subjects exhibited worse N-back test accuracy during **dual-task obstacle-crossing** compared to **single-task N-back.** This keeps in line with how motor function detracts from cognitive function (Srygley et. al., 2009). Conversely, **pre-fatigued** subjects exhibited worse N-back test accuracy during **single-task N-back** compared to **dual-task walking.** This result is challenging to explain as most literature on dual-task walking finds cognitive performance is adversely affected when subjects concurrently walked (or obstacle-crossed). I could propose that walking somehow exhibited a calming and focusing effect on the working memory test, but this is difficult to validate with current literature. I once again reference how light aerobic exercise may temporarily improve cognitive performance in healthy young adults (Kamijo et. al.,

2009), although this effect seems unlikely to manifest in rested subjects who are only at that moment preforming extremely light exercise in the form of walking.

Fatigue Protocol

According to previous studies (Barbieri et. al., 2013, 2013, 2016), mean duration of the sit-to-stand fatigue protocol has ranged from 6.7 to 17.0 minutes in healthy young adults. In this study, 24 subjects fatigued in 24.9 ± 8.4 minutes. This longer time could be a reflection on a number of factors including but not limited to the activity level of recruited subjects, the provided water and fan, or the verbal encouragement from both researchers during the fatigue protocol.

Subjects performing longer time during the fatigue protocol do not necessarily mean they experienced greater fatigue; if the subject pool on average was more active and fitter, they might also handle fatigue better than less active subjects. Furthermore, a longer average time to fatigue also means many of our subjects performed until the cut-off of 30 minutes, raising the question of whether they were truly fatigued by the end of the protocol. If a significant number of subjects were not truly fatigued by the end of the protocol, they might alter the data to reflect fewer significant differences of variables between pre-fatigue and post-fatigue.

Indeed, the study continued on even when the subject exhibited less than 25% strength drop in flexion and extension. However, there was an average drop of $22.8 \pm 5.9\%$ muscle extension strength after the fatigue protocol, which recovered to a drop of $14.2 \pm 9.9\%$ by the end of the experiment. This assuages apprehension our fatigue protocol was too easy and did not allow for significant fatigue. Muscle flexion strength

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was on average not affected by the fatigue protocol (flexion strength *gain* of $1.4 \pm 8.6\%$ with recovery a *drop* of $0.7 \pm 9.6\%$).

We chose to implement a sit-to-stand fatigue protocol in order to induce lower limb fatigue. However, how to best fatigue a subject is a controversial topic, especially when considering the context of the experiment and what we are trying to mimic with this fatigue. Our study is concerned with populations which are susceptible to fatigue, such as labor-intensive workers. Unfortunately, it is not practical to ask subjects to perform a labor-intensive activity over the course of a few hours in order to mimic a worker's conditions of continuous labor. The sit-to-stand fatigue protocol achieves primarily lower limb fatigue in a short amount of time. Furthermore, this protocol targets muscle abilities, rather than cardiorespiratory capabilities, meaning when a subject reaches their limit and signals a quit we are inclined to attribute their reason to muscular rather than cardiorespiratory limits. Running is a popular fatigue protocol, but our study dismissed it as a possibility due to the high amount of cardiorespiratory ability required. We aimed to mimic populations who are on their feet and walking around all day, thus a lower limb fatigue protocol was selected.

Conclusion

Daily activities and jobs which require walking and stepping over low obstacles are extremely prevalent. Unfortunately, these motor activities result in staggeringly high falling accidents. Muscular fatigue from movement throughout the day may increase the risk of falls. Engaging in working memory tasks may detract from motor control. During daily jobs and activities, working memory tasks may interact with walking and obstacle-crossing, with and without the debilitating effects of muscular fatigue. In order to address falling incidents, these conditions need to be investigated for main and interaction effects. In this study, gait characteristics of walking and obstacle-crossing in healthy young adult are shown to be significantly affected by fatigue and dual-task conditions in numerous variables.

Slowing gait speed and decreasing stride length during dual-tasks may minimize motor action and protect against mis-navigating terrain, reducing the risk of tripping. Greater clearance of the leading and trailing foot over an obstacle during dual-task likely reduces the probability of tripping and is an unconscious effect. Placing the leading foot closer to an obstacle after crossing during dual-task minimizes balancing time over the obstacle and may reduce the risk of becoming destabilized and subsequently falling.

Faster gait velocity and wider step widths when fatigued are likely unconscious effects and may increase risk of tripping. Placing the leading foot closer to an obstacle after crossing when fatigued suggests inability to more fully and successfully surmount an obstacle and may increase the risk of tripping. A greater peak forward velocity when fatigued suggests sharper movements and reduced smoothness of gait, likely stemming

from an inability to stabilize movement due to muscular fatigue, thus increasing the risk of mis-navigating difficult terrain and subsequently tripping.

In this study, working memory tasks are also shown to be affected by fatigue and concurrent walking or obstacle-crossing and their interaction. Working memory by itself is adversely affected by fatigue. Walking and performing working memory tasks when fatigued negatively affected working memory. When fatigued, an additional working memory task while walking or obstacle-crossing negatively affects working memory performance. When rested, working memory improves with concurrent walking; conversely, when rested, working memory worsens with concurrent obstacle-crossing.

Appendix A

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University of Oregon

Department of Human Physiology

Name of study	Muscle fatigue
Purpose of study	To investigate how muscle fatigue affects gait characteristics and cognitive performance during walking and obstacle-crossing
Location of study	Motion Analysis Laboratory (B52 Gerlinger Annex)

Specific requirements

Inclusion criteria
- **18-40 years old**
- **Able to walk over ground and cross over an obstacle without an assistive device**
- **Normal hearing**

Exclusion criteria
- **History of neurological disease or injuries including head trauma**
- **Impairments involved with bones, muscles, or joints within the past six months**
- **Persistent symptoms of dizziness, lightheadedness, unsteadiness, or any other medical condition that may affect your ability to walk over ground or cross over an obstacle**
- **Consume of any alcohol or caffeine 24 hours prior to the examination**
- **Any strenuous activity 24 hours prior to the examination**

Type of activity	Walking, crossing-obstacle, muscle strength test, auditory cognitive test, repeated sit-to-stand motion
Approximate length of time	1.5-2 hours
Payment	$ 10/hour
Contact information	Name: Teresa Chen
	Email: szuhuac@uoregon.edu
	TEL: 541-346-1033

Muscle fatigue szuhuac@uoregon.edu 541-346-1033 (repeated tear-off strip, vertical text) ×13

Appendix B

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ID:_____   **Date:**_____

University of Oregon
Department of Human Physiology
Informed Consent for Participation as a Subject in
Effects of Muscle Fatigue on Gait and Cognitive Functions
Investigator: Szu-Hua Chen
Type of consent Adult Consent Form

Introduction
- You are being asked to be in a research study of effects of muscle fatigue on human motion and cognitive function.
- You were selected as a possible participant because you are a healthy individual aged 18-40 years. However, if you do not pass the screening test, you will be excluded from participation in this study.
- We ask that you read this form and ask any questions that you may have before agreeing to be in the study.

Purpose of Study:
- The purpose of this study is investigate the effects of muscle fatigue on motion and cognitive performance, measured by gait and auditory cognitive test, under single and dual-task condition.
- Participants in this study are from local community (mainly at the University of Oregon). The total number of subjects is expected to be 24.

Description of the Study Procedures:
- If you agree to be in this study, we would ask you to do the following things:

You will visit the Motion Analysis Laboratory (B52 Gerlinger Annex) once. The total data collection will take approximately 2 hours. All of the data collected is coded and therefore we maintain all personal confidentiality.

Screening session
At the beginning, you will be asked to complete this consent form and the "Habitual Physical Activity and Healthy History Questionnaire". If you answer yes in any of the questions under health history section, you will be excluded from participation in this study. If you pass the screening test, you will continue to the testing sessions. The screening session will take approximately 10 minutes.

Preparation session
You will first be directed to change into shorts and a tank top. Your age, height, and weight will then be measured. Further, the length and width of your feet, the medio-lateral dimensions of your ankle joints, knee joints and your pelvic width will also be measured. The entire preparation session will take approximately 10 minutes.

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Reflective marker placement

A set of 29 reflective markers will be placed on bony landmarks of your body. It will take 5 minutes.

Practice N-back test

You will practice the N-back Test. In this N-back Test, you will hear a series of recorded numbers and recognize the repetition of a number from n number ago. For example, if n = 2, and the number sequence is 1, 2, 1, you will have to answer "yes" when you hear the "1" again since the 1 is repeated from 2 numbers ago.

Pre-fatigue measurement

You will be asked to perform the following tasks in random order: (1) sitting while responding to the N-back test, (2) walking, (3) walking while responding to the N-back test, (4) obstacle-crossing, (5) obstacle-crossing while responding to the N-back test. Each task takes about 2-3 minutes. Detailed information of each task is presented as follows.

Sitting while responding the N-back test

You will be asked to sit and to complete 2-minute of the N-back test. This task will take about 3 minutes and will be conducted before and after muscle fatigue.

Level Walking and Obstacle-Crossing Tasks

You will be asked to walk along a 10-meter walkway and cross over an obstacle with or without the N-back test. The obstacle will be presented as a PVC pipe bar. You will be walking over ground and crossing over an obstacle for several times until you feel comfortable walking with the markers and with your self-selected speed. After you are comfortable, you will cross the obstacle and walk over ground with the N-back test concurrently. These tasks will take about 12 minutes and will be conducted before and after muscle fatigue.

Muscle strength test

You will sit and be restrained on a dynamometer with your right ankle fixed with the cuff placed 2 cm above the lateral malleolus. During the test, you will be instructed to bend or straighten the right knee as hard as possible for 5 seconds. Prior to test, you will be allowed to do practice trials for 2-3 times. A total of 3 knee bent and 3 knee straight motions with a 1-minute rest between each movement will be acquired. These tasks will take about 5 minutes and will be conducted before, after muscle fatigue and in the end of procedure.

Fatigue protocol

You will be asked to sit on a chair without armrest with arms across the chest. You will hear beat sounds generated from a metronome at pace of 0.5 Hz while following the pace to do a repeated sit-to-stand motions. The fatigue protocol will be stopped when you indicate that you are unable to continue, when the movement frequency falls below 0.5 Hz after encouragement, or after 30 min. The time this task will take depends on your fatigability.

Marker Removal

Markers will be removed from you after completing the aforementioned tasks.

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Risks/Discomforts of Being in the Study:
- The study has the following risks. First, during the walking and obstacle-crossing tasks, we expect there will be no more risk for you than there normally is for you when outside of the laboratory. Second, lower limb muscle fatigue induced by the fatigue protocol may cause temporary soreness. **You will be given frequent breaks as requested during the experiment. If you have any questions or concerns after the experiment, please call the Principle Investigator. Third**, there is also a possibility of discomfort involved in removing adhesive tape (used for marker) from skin at the end of the experiment. However, our staff member will minimize the potential discomfort with a non-allergic tape. Last but not least, all information will be kept confidential. Computer data files, laboratory notes and videotapes will be archived in a locked filing cabinet. All records will be stored with a code number, not your name, and will be kept by the principal investigators in the locked and security-regulated Motion Analysis Laboratory.

Benefits of Being in the Study:
- The purpose of the study is to investigate how muscle fatigue affects gait characteristics and cognitive performance during walking and obstacle-crossing.
- Although you personally will not receive any benefits from this research, based on results of this study more effective therapies, rehabilitation programs, or balance assistive devices for the prevention of falls in a number of patient populations may be designed and implemented.

Payments:
- **You will be provided a check of $20 at the completion of all testing procedures.** This is to help defray the costs incurred for participation such as parking and transportation as well as your time. **Under any circumstances if you do not complete the study, you will receive a partial compensation of $10.**

Costs:
- There is no cost to you to participate in this research study.

Confidentiality:
- The records of this study will be kept private. In any sort of report we may publish, we will not include any information that will make it possible to identify a participant.
- Your name will be replaced by code numbers. The code numbers matching particular data sets to individual subjects will be stored in a hard copy. The hard copy will be kept in a locked filing cabinet separate from the data itself and only the principal investigator, co-investigators, and graduate students involved in this project will have access to it.
- The cameras used for the study only can record markers attached to your bony landmarks and none of your image in a recognizable way will be recorded. All electronic information will be coded and secured using a password protected file.
- All laboratory notes will be archived in coded form in a locked filing cabinet and security regulated Motion Analysis Laboratory (B52, Gerlinger Annex).
- No identifiable information other than name will be retained after data is gathered from you. At the completion of the study and after the results have been published, the list of participants' names will be destroyed.

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- Access to the data, records and code numbers will be limited to the researchers; however, please note that the Institutional Review Board and internal University of Oregon auditors may review the research records.

Voluntary Participation/Withdrawal:
- Your participation is voluntary. If you choose not to participate, it will not affect your current or future relations with the University of Oregon.
- You are free to withdraw at any time, for whatever reason.
- There is no penalty or loss of benefits for not taking part or for stopping your participation. If you are a student of the University of Oregon, you do not jeopardize grades nor risk loss of present or future faculty/school/University relationships due to early withdrawal.

Dismissal From the Study:
- The investigator may withdraw you from the study at any time for the following reasons: (1) withdrawal is in your best interests (e.g. side effects or distress have resulted, or (2) you have failed to comply with the study requirements.

Contacts and Questions:
- The researchers conducting this study are Teresa Chen and Dr. Li-Shan Chou. For questions or more information concerning this research you may contact her/him at 541-346-1033 and 541-346-4311.
- If you believe you may have suffered a research related injury, contact Teresa Chen at 541-346-1033 who will give you further instructions.
- If you have any questions about your rights as a research subject, you may contact: Research Compliance Services, University of Oregon at (541) 346-2510 or ResearchCompliance@uoregon.edu

Copy of Consent Form:
- You will be given a copy of this form to keep for your records and future reference.

Statement of Consent:
- I have read (or have had read to me) the contents of this consent form and have been encouraged to ask questions. I have received answers to my questions. I give my consent to participate in this study. I have received (or will receive) a copy of this form.

Signatures/Dates

_____

Study Participant (Print Name)

_____

Participant or Legal Representative Signature

Date

Appendix C

Date:
_____

Habitual Physical Activity and Healthy History Questionnaire

Part 1: Habitual Physical Activity

Please, make a circle around the appropriate answer for each question, considering the past 12 months:

1. Do you or did you practice sports or physical exercise within the past 12 months: yes/no Which sport or physical exercise do you or did you practice more often? _____ – how many hours a week? _____ – how many months a year? _____ If you practice or practiced a second modality of sport or physical activity, what is it? _____ – how many hours a week? _____ – how many months a year? _____					
2. When compared to others of my age, I think my physical activity during leisure hours is: much more/more/the same/less/much less	5	4	3	2	1
3. During leisure hours, I sweat: very often/often/sometimes/seldom/never	5	4	3	2	1
4. During leisure hours, I practice sports or physical exercises: never/seldom/sometimes/often/very often	1	2	3	4	5
5. During leisure time, I watch TV: never/seldom/sometimes/often/very often	1	2	3	4	5
6. During leisure hours, I walk: never/seldom/sometimes/often/very often	1	2	3	4	5
7. During leisure hours I ride a bike: never/seldom/sometimes/often/very often	1	2	3	4	5
8. For how many minutes a day do you walk or ride a bike going back and forth from work, school or shopping? Total in minutes: _____ < 5/5-15/16-30/31-45/> 45	1	2	3	4	5

(continue)

Part 2: Healthy History

Have you been under recent medical care for any of the following conditions?

1. Neurological disorder? If yes, is your daily function moderately or significantly impaired? _____	YES NO
2. A significant head injury? If yes, is your daily function moderately or significantly impaired? _____	YES NO
3. Hearing impairment? If yes, is your daily function moderately or significantly impaired? _____	YES NO
4. Muscle, joint, or other orthopedic disorder? If yes, is your daily function moderately or significantly impaired? _____	YES NO
5. Persistent vertigo, lightheadedness, unsteadiness, or falling? If yes, is your daily function moderately or significantly impaired? _____	YES NO
6. Any other medical conditions that may affect you to walk over ground or cross an obstacle? If yes, please describe _____	YES NO

Part 3: Fatigue-related Questions

1. Did you consume of any alcohol or caffeine within 24 hours?	YES NO
2. Do you do any strenuous activity 24 hours?	YES NO

Appendix D

Date:		File:							R	L	**cm**		
Sex:		(i.e. Fatigue_01)				Ft Length							
Subject ID			Age (yr)			Ft Width					mm	mm	
Birthday			Ht (cm)			Knee Width							
			Wt (kg)			Ankle Width							
						ASIS Width							
Trial Cond.	R/L FS	Cortex Trial #	THS	LTO	LHS	TTO	THS	LTO	.trb	.anc	.trc	Matlab	
static		1											
static		2											
static		3											
static		4											
static		5											
pre_Nback		1											
pre_walk		1											
pre_walk		2											
pre_walk		3											
pre_walk		4											
pre_walk		5											
pre_walk													
pre_walk													
pre_walk													
pre_walk													
pre_walk_N		1											
pre_walk_N		2											
pre_walk_N		3											
pre_walk_N		4											
pre_walk_N		5											
pre_walk_N													
pre_walk_N													
pre_walk_N													
pre_obs		1											
pre_obs		2											
pre_obs		3											
pre_obs		4											
pre_obs		5											
pre_obs													
pre_obs													
pre_obs													
pre_obs													
pre_obs_N		1											
pre_obs_N		2											
pre_obs_N		3											
pre_obs_N		4											
pre_obs_N		5											
pre_obs_N													
pre_obs_N													
pre_obs_N													

Trial Cond.	R/L FS	Cortex Trial #	THS	LTO	LHS	TTO	THS	LTO	.trb	.anc	.trc	Matlab
post_Nback		1										
post_walk		1										
post_walk		2										
post_walk		3										
post_walk		4										
post_walk		5										
post_walk												
post_walk												
post_walk												
post_walk_N		1										
post_walk_N		2										
post_walk_N		3										
post_walk_N		4										
post_walk_N		5										
post_walk_N												
post_walk_N												
post_obs		1										
post_obs		2										
post_obs		3										
post_obs		4										
post_obs												
post_obs		5										
post_obs												
post_obs												
post_obs_N		1										
post_obs_N		2										
post_obs_N		3										
post_obs_N		4										
post_obs_N		5										
post_obs_N												
post_obs_N												
			1	2	3							
	MVC1	knee extension										
		knee flexion										
	MVC2	knee extension										
		knee flexion										
	MVC3	knee extension										
		knee flexion										
Time to fatige (min'sec")												
Nback	pre_walk											
	pre_obs											
	post_walk											
	post_obs											

Appendix E

Subject ID: _____
Date: _____

Task																										
3-back Practice																										
2	4	5	2	9	8	6	7	1	6	5	4	3	3	4	2										
3-back Trial 1																										
1	2	9	4	7	8	4	2	5	1	3	5	2	9	6	7	9	5	3	8	4	5	8	1	6	2
3-back Trial 2																										
8	3	4	6	7	4	3	1	6	8	9	6	5	8	3	7	6	2	7	1	4	2	9	3	6	4
3-back Trial 3																										
6	7	3	3	5	9	6	4	3	6	9	1	8	5	7	2	5	4	3	9	3	8	9	2	5	6
3-back Trial 4																										
8	1	4	8	4	5	7	5	3	8	5	7	7	6	1	3	2	1	2	7	8	2	4	9	1	7
3-back Trial 5																										
4	8	3	3	8	5	1	7	2	4	7	6	7	3	9	9	5	3	8	5	6	9	1	2	3	7
3-back Trial 6																										
5	2	9	6	8	9	4	4	2	5	1	3	6	1	4	3	7	4	6	9	3	2	6	4	2	9
3-back Trial 7																										
8	1	7	8	4	5	1	1	3	4	9	2	4	6	4	3	3	1	8	2	5	9	6	5	3	2
3-back Trial 8																										
1	5	4	3	2	9	7	5	3	8	5	8	1	6	3	1	2	6	9	9	6	3	7	4	2	1
3-back Trial 9																										
7	9	6	8	4	2	8	3	5	1	3	9	2	8	6	7	8	4	2	7	3	5	7	5	9	8
3-back Trial 10																										
3	7	9	3	5	1	8	7	2	3	4	2	1	9	7	3	9	8	4	5	1	6	2	7	4	3

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