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Eye-Hand Coordination Varies According to Changes in Cognitive-Motor Load and Eye Movements Used

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EYE-HAND COORDINATION VARIES ACCORDING TO CHANGES IN COGNITIVE-MOTOR LOAD AND EYE MOVEMENTS USED

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NOMENCLATURE

ACSM–American College Of Sports Medicine

AE–Absolute Endpoint Error

aIDE–Absolute Initial Direction Error

CoP–Center Of Pressure

DMN–Default Mode Network

EEG–Electroencephalography

EFR–Eyes Fixated, Hand Moves Away From Target

EH–Eye-Hand Coupling, Involving Eye-Hand Moving Towards Target Together

EHR–Eye-Hand Decoupling, Involving Eyes Moving Towards Target and Handy Away From Target

EMG–Electromyography

ERHR–Eye-Hand Coupling, Involving Eyes and Hand Moving Away From Target

ERP–Event-Related Potentials

FH–Eyes Fixated, Hand Moves Towards Target

FFT–Fast Fourier Transformation

IPAQ–International Physical Activity Questionnaire

LSU–Louisiana State University

MT–Movement Time

nAP–Normalized Anterior-Posterior Displacement

nML–Normalized Medio-Lateral Displacement

nRD–Normalized Radial Displacement

VEL–Average Center Of Pressure Path Length Per Second

PCC–Posterior Cingulate Cortex

PL–Path Length

PV–Peak Velocity

RespT–Response Time

RPE–Ratings Of Perceived Exertion

RT–Reaction Time

SAC–Group Saccades

SmP–Group Smooth Pursuit

SR–Spatial Reconstruction Task

ABSTRACT

In this dissertation three studies were used to help improve the understanding of eye-hand coordination control of visuomotor reaching tasks with varying cognitive loads. Specifically, we considered potential performance differences based on eye-movements, postural influences, as well as fitness level of the young adult participants. A brief introduction in chapter 1 is followed by a detailed literature review in chapter 2. Results from the three studies presented in chapter's 3-5 further advance our knowledge of the integrated control used for goal-directed visually-guided reaches. In the first study (chapter 3), the additional cost associated with the use of smooth pursuit slowed hand movement speed when the eyes and hand moved in distinct directions, yet improved accuracy over the use of saccadic eye movements and eye fixation. We concluded that eye-movement choice can influence various types of visually-guided reaching with different cognitive demands and that researchers should provide clear eye-movement instructions for participants and/or monitor the eyes when assessing similar upper limb control to account for possible differences. In the second study (chapter 4), results revealed slower speed and poor accuracy of hand movements along with less body sway for visually-guided reaching when the eyes and hand moved in opposite directions during eye-hand decoupling compared to when the eyes and hand moved in the same direction (eye-hand coupling). In contrast, standing up did not significantly influence reaching performance compared to sitting. We concluded that increases in cognitive demands for eye-hand coordination created a greater need for postural control to help improve the goal-directed control of reaching. In the third study (chapter 5), we found no evidence of eye-hand coordination differences between highly fit or sedentary participants, yet cerebral activation in

the centro-parietal location differed between tasks involving eye-hand coupling/decoupling. We concluded that reaching performance declines accompanied increased sensorimotor demands during eye-hand decoupling that may link to prior/current athletic experience and not fitness level. Overall, alterations in visually-guided goal-directed reaching movements involving eye-hand coupling and decoupling depend on changes in eye-movements utilized and not on low threat postural changes or fitness levels of the young adults performing the task.

CHAPTER 1: INTRODUCTION AND SIGNIFICANCE

Movements of human eyes and hands occur together, and separately, when performing a variety of monotonous (i.e. washing hands) and skillful (i.e. juggling or playing an instrument) tasks. To what extent do each influence human movement and sensorimotor control? This question has driven and continues to drive motor control research. The effect of eye-hand coordination on human movement comprises one area heavily researched in the field of motor control. Researchers reveal that eye movements (saccades, smooth pursuit, and fixations) can influence multiple aspects of reaching tasks (Gribble, Everling, Ford, & Mattar, 2002; Neggers & Bekkering, 2002; Snyder, Calton, Dickinson, & Lawrence, 2002). Additionally, separating movement of the eyes from hand movements spatially during a reaching task, known as decoupling, can provide vital information about the sensorimotor systems and how they control/influence movement (Tippett, Krajewski, & Sergio, 2007; Salek, Anderson, & Sergio, 2011); Hawkins & Sergio, 2014). However, results from extensive research on eye-hand decoupling tasks do not begin to address how different eye movements (i.e. saccades, smooth pursuit, or fixations) influence temporal and spatial aspects of hand movements during decoupling tasks.

One goal of this document includes a summary of the literature on eye-hand coordination involving coupling vs decoupling effects on human performance. Specifically, we chose to determine how eye movements (i.e. saccades, smooth pursuit, and fixations) can influence hand movements during eye-hand coordination. Identifying gaps in the literature will help to shape research ideas and form questions needed to design and conduct future studies. Identifying how various eye movements influence hand movements is valuable because of its

daily use and application to neurological populations, who often experience early deterioration in eye-hand coordination (e.g., (Hawkins & Sergio, 2014)). Understanding more about such coordination will likely provide additional information as to why certain neurological populations are plagued by these deficits and provide a basis for establishing rehabilitation techniques to minimize coordination declines.

Eye movements, which influence hand movements, can also influence postural sway (Tanaka & Uetake, 2005; Rougier & Garin, 2007; Stoffregen, Bardy, Bonnet, Hove, & Oullier, 2007; Ajrezo, Wiener-Vacher, & Bucci, 2013; Rodrigues et al., 2013; Rodrigues et al., 2015; S. Y. Kim, Moon, & Cho, 2016; Yeomans, Nelson, MacLellan, & Hondzinski, 2018). Thus, another goal of this document involves review of the literature on the potential bidirectional influences between standing posture and eye-hand coordination. Common eye-hand coordination tasks often include standing; however, the majority of eye-hand coordination experiments involve seated participants. Therefore, reviewing literature on eye movement influences on standing posture and/or eye-hand coordination changes from sitting to standing positions will help expand our knowledge in this area. Also, if bidirectional influences exist, performing eye-hand coordination tasks while standing may provide a more sensitive measures for detecting neurological declines in various populations. For example, even if sedentary people with neurological declines due to peripheral neuropathy in the lower limbs successfully perform the decoupled eye-hand coordination tasks while sitting, difficulties could arise when performing the tasks while standing. Deficits with multitasking, yet not in single task performances for young, adult males (Dierijck, Kennefick, Smirl, Dalton, & van Donkelaar, 2019) provides evidence for such a possibility.

With expected neurological influences on eye-hand coordination comes the responsibility of identifying ways to avoid or correct neurological decline. Improving aerobic fitness may provide the solution to correcting eye-hand sensorimotor task deficits in certain neurological populations. Increased aerobic fitness levels which influence fronto-parietal connectivity (Raichlen et al., 2016), possibly due to increased brain oxygenation (Dupuy et al., 2015), exist, thus could serve as a rehabilitation tool for some people with sensorimotor deficits.

CHAPTER 2: REVIEW OF LITERATURE

Introduction

The purpose of this chapter is to review the research on cognitive functions, eye-hand coordination, and how these topics interact with postural control in healthy and special/neurological populations. This literature review will provide vital information about how eye movements influence eye-hand coordination, how sensitive posture is to the performance of certain tasks, and how human movement/cognitive processing is different between various populations. This review will also discuss how cerebral activations and connectivity are altered during the performance of various tasks, and how these activations or functional connections change between different populations.

Eyes and Hand

Visual Inputs and Eye Movements

Visual inputs during saccades, smooth pursuit, and fixations may influence various aspects of movement from standing posture (Rodrigues et al., 2015) to goal-directed reaching tasks (Engel & Soechting, 2003). Understanding how eye movements, with the use of visual inputs, influence body movement during standing and/or reaching tasks will add to our current knowledge of how the eyes, hand, and body interact during movement. A brief overview of certain eye movements provides the background information needed to better understand movement coordination involving the eyes.

- *Saccadic* eye movements involve repositioning the eyes on a new target (Purves, Augustine, Fitzpatrick, & editors, 2001).
- *Smooth pursuit* eye movements involve visual tracking of a moving target (Purves et al., 2001).

- *Fixations* involve positioning the eyes on a stationary target for an extended period of time. The *vestibulo-ocular reflex (VOR)* and *optokinetic reflex (OKR)* allow such stabilization during relatively fast (which uses the vestibular system) and slow (uses visual feedback) head movements, respectively.

Visual Inputs/Eye Movements Effect on Posture

Use of visual inputs while standing reduces sway compared to performances without vision (Tanaka & Uetake, 2005). Control of human eye positioning can also play a role in attenuating postural sway (Fox, 1990; Rodrigues et al., 2015; S. Y. Kim et al., 2016). Fixation of gaze on a point in the environment can decrease postural sway compared to the use of free gaze (Paulus, Straube, & Brandt, 1984; Strupp et al., 2003). Previous studies reveal that use of visually-guided saccades can attenuate postural sway equal to (Rey, Le, Bertin, & Kapoula, 2008; Thomas, Bampouras, Donovan, & Dewhurst, 2016) or better than (Rougier & Garin, 2007; Stoffregen et al., 2007; Ajrezo et al., 2013; Rodrigues et al., 2013; Rodrigues et al., 2015; Yeomans et al., 2018) the use of a simple fixation point. This saccadic effect on postural sway holds true when performing slow or fast saccades (Stoffregen et al., 2007; Rodrigues et al., 2013; Rodrigues et al., 2015), vertical or horizontal saccades (Rey et al., 2008); and medium (Stoffregen et al., 2007; Rodrigues et al., 2013; Rodrigues et al., 2015) or relatively large (Rey et al., 2008) amplitude saccades. Smooth pursuit eye movements may (Rodrigues et al., 2015) or may not (Kim et al., 2016) decrease standing sway. Combining various eye movements during performance of coupled and decoupled eye-hand coordination tasks would offer opportunities to study control of these integrated movements. Comparisons of postural sway while performing coupling/decoupling tasks may also be of interest.

Eye-Hand Coordination

Visuomotor integration

Performance of motor skills often relies on integration of hand and eye movements. These skills can vary from reaching tasks to more complex movements. Hand placement near a visual stimulus appears to reduce the variability of V2 neurons compared to when the hand is not visually present in monkeys (Perry, Sergio, Crawford, & Fallah, 2015). This study reveals a strong link between the hand and eyes, which suggests the importance of integrating the eyes and hand when performing a reaching task. Use of visual and proprioceptive information improves spatial accuracy performance compared to the use of purely proprioceptive cues (i.e. no visual feedback), emphasizing the importance of visual information for motor tasks (Ren et al., 2006).

Eye-Hand Coupling

Coordination of eye-hand movements occurs when moving to stationary or moving targets. Although the eyes typically initiate movement to an intended stationary target before the hand (Angel, Alston, & Garland, 1970), Gribble et al. 2002 revealed that electromyography (EMG) onset of the reaching limb actually precedes initiation of saccadic eye movements to suggest preprogramming of the limb, before movement initiation. In humans, coupling the eyes and hand together can decrease hand latency and increase latency of the eyes compared to tracking a moving target using only the hand or eyes (smooth pursuit), independently (Engel & Soechting, 2003). In monkeys, coupling the eyes and hand when reaching toward a moving target allows for greater speed of saccadic eye movements, up to four percent faster than decoupling movements (Snyder et al., 2002). Moving the eyes and hand in the same direction

may slow the response of the eyes but increase their speed along with the response of the hand for certain eye movements.

Eye-Hand Decoupling

The eyes and hand are normally tightly coupled during reaching movements, but the two can be separated to perform a precise reaching task (Foerster, 2016). Adam et al. 2012 showed that if the hand and eyes start in different places before looking at and reaching to a final target then an early onset of the eyes accompanied a late onset of the hand. Although decoupled task performances can reveal similar spatial accuracy to coupled tasks, temporal aspects of movement seem to degrade often. Moreover, use of a decoupled task can reveal examples of degraded movement from spatial and temporal aspects. In fact, researchers continue to explore the results of decoupled movements to help explain the integration of cognitive and motor systems.

Cognitive-motor Integration and Special Populations

Cognitive-motor Integration (CMI) research involves upper limb and eye movements. CMI tasks can vary in how these movements integrate to alter the complexity of visually guided motor tasks. The eyes and hand either move in similar or different directions to present or remembered targets (Salek et al., 2011; Brown, Dalecki, Hughes, Macpherson, & Sergio, 2015; Hawkins & Sergio, 2014) and are performed in a vertical or horizontal plane (Salek et al., 2011; Brown et al., 2015; Hawkins & Sergio, 2014). Increasing complexity of the task, decoupling the eyes and hand, moving to remembered targets (Salek et al., 2011; Brown et al., 2015), or performing horizontal plane movements while viewing vertical plane presentations (Salek et al., 2011; Brown et al., 2015; Hawkins & Sergio, 2014), will correspond to worse performance on

reaction time and movement time, especially if the people present with neural deficits (Brown et al., 2015; Hawkins & Sergio, 2014; Salek et al., 2011). In contrast, no differences or minimal differences between healthy and neurological populations exist when performing a coupled task.

Visual motor deficiencies occur in multiple populations including people with mild cognitive impairments (Salek et al., 2011), Alzheimer's patients (Hawkins & Sergio, 2014), concussed athletes (Brown et al., 2015), and concussed children (Dalecki, Albines, Macpherson, & Sergio, 2016) to differentiate populations with specific neurological damage from healthy populations. Deficiencies in decoupled movements leads to an increase in reaction time and movement time for people with mild cognitive impairments (MCI) compared to healthy controls to indicate a usefulness of visual motor integration via CMI to help in predicting early cognitive decline (Salek et al., 2011). Fronto-parietal network impairment associates with worse decoupled CMI performances in people with Alzheimer's disease (Hawkins, Goyal, & Sergio, 2015), thus is proposed as the damaged network in others with poor CMI performance.

The research mentioned previously reveals the importance of visual, motor, and cognitive integration in performing an eye-hand coordinated task. However, for many of these studies, researchers do not consider how the type of eye movements (saccades, smooth pursuit, or fixations) influence CMI task performances or provide information about which type of eye movements are predominately used during their performance. Researchers in this area also do not control the eye movements used during the task performances, nor do they address the underlying mechanism used for the decoupling tasks that might result in movement deficiencies. Although the type of eye movement may not matter for performance outcomes,

the strongest CMI differences observed may relate to how closely linked the hand and eye are during movement. For instance, the eyes often move faster to a target when coupled with the hand using saccades (Snyder et al., 2002) and this could potentially result in faster hand responses or movement times, which would likely differ if using smooth pursuit. Eye movement could explain the faster eye-hand integration contributing to the quicker temporal measures observed in CMI research when comparing coupled versus decoupled tasks.

Brain Imaging For Eye-Hand Tasks

Multiple types of brain imaging techniques exist and can be used to determine how brain activation changes during performances of specific tasks. The text in this section reveals results from studies, which use imaging techniques to investigate brain activation during eye-hand coordination tasks.

Functional Magnetic Resonance Imaging (fMRI)

Functional magnetic resonance imaging (fMRI) technology is a viable tool with good spatial accuracy for observing brain activation due to the change in response from hydrogen nuclei after absorbing a magnetic pulse during movement and non-movement tasks. Movement restrictions associated with fMRI technology (i.e. too much head movement does not give an accurate depiction of activation) limits its use to movements performed while lying down with a stationary head. Results from fMRI research reveal that the dorsal stream plays a vital role in using visual information to assist the generation of a hand movement (Ellermann, Siegal, Strupp, Ebner, & Ugurbil, 1998). Cerebellar activation increases when performing a novel eye-hand coordination task (Miall & Jenkinson, 2005) or an eye-hand coordination tasks compared to isolated eye movement or hand movement tasks (Nitschke, Arp, Stavrou,

Erdmann, & Heide, 2005). The latter authors also showed that increasing the cognitive demand of a task leads to greater activation in the cerebellum to suggest an important role of the cerebellum during CMI task performances.

Coupled and decoupled CMI tasks performed on a vertical or horizontal plane may influence cortical activity differently. Gorbet et al. 2019 showed that performances in a coupled task, compared to a decoupled task involving a plane-change (hand movements in a horizontal plane with eye movements on in a vertical plane), corresponded to different brain activity patterns in the frontal, parietal, occipital, and cerebellar areas (Gorbet & Sergio, 2019). Although similar cortical activation existed during early movement preparation of coupled and decoupled tasks, activation differed during late movement preparation and during movement execution. Gorbet et al. 2016 show that decoupling of the eye and hand resulted in greater parietal and cerebellum activity compared to coupled movements (Gorbet & Sergio, 2016). These studies provide crucial information about brain activation patterns during performances of CMI tasks. While researchers often refer to these tasks as cognitive-motor integration tasks, it is important to remember that sensory information and activation of sensory areas play a major role in task performance.

While no cortical activity differences between left- and right-handed individuals exist for CMI task performances to date, other eye-hand coordination task performances show a difference in cortical activity patterns between left- and right-handed task completion. Specifically, distinct cortical activity pattern differs between left-handed and right-handed goal-directed movements, regardless of whether an individual is left- or right-handed (Lavrysen et al., 2012). As a result, ensuring same handed participants use the same hand within a study and

questioning results in studies using mixed handedness and/or mixed hands used for task performances seems reasonable.

Functional Near Infrared Spectroscopy (fNIRS)

A few researchers use functional near infrared spectroscopy (fNIRS) technology to track blood hemoglobin and determine the influence eye-hand coordination movements on brain oxygenation levels, thus neural activity. Although fMRI spatial accuracy exceeds that of fNIRS, the portability of fNIRS equipment makes it ideal for tasks requiring head and/or large body movements. For example, steering tasks with greater attentional demands, due to incongruent steering (reversed steering: right becomes left, and left becomes right using keyboard arrows) and/or varied acceleration, invoked greater oxygenation in the right superior parietal lobule compared to congruent steering and constant velocity conditions (Hosseini et al., 2017).

Performing CMI tasks while standing/walking, and while monitoring brain oxygenation using fNIRS technology, may provide cortical activation differences between people with and without neurological deficits. Difficult balancing trials, described as skill level ranging from beginner to advanced (advanced being more difficult) on a Wii skiing game, leads to greater activation of blood flow in the superior temporal gyrus of healthy adults (ages ranging from 18-42 years), compared to less difficult tasks (Karim, Schmidt, Dart, Beluk, & Huppert, 2012). These results indicate that fNIRS equipment can register greater oxygenation used for sensorimotor integration during difficult balancing task performance in healthy individuals.

Electroencephalographic (EEG)

Unlike fMRI and fNIRS research, electroencephalographic (EEG) technology emphasizes temporal occurrences of electrical cortical activation during varied types of human movement

called event related potentials (ERPs) (Wehrspaun, Pfabigan, & Sailer, 2013). Lebar et al. 2015 showed that greater amplitudes of visual-evoked potentials exist in specific occipital/temporal regions during successful completion of normal verses reversed visually-guided hand movement tasks. Greater potential amplitudes may indicate greater control of visually-guided movements (Lebar, Bernier, Guillaume, Mouchnino, & Blouin, 2015), but further studies are needed to confirm this assumption. Younger adults revealed increases in beta rhythm, increases in beta wave amplitudes synchronization, in sensorimotor areas compared to older adults after completing a reaching/pointing task using similar movement durations (Labyt et al., 2003). Increased beta rhythms in sensorimotor areas may represent increased abilities to process multiple afferent inputs, suggesting greater sensory-motor integration in younger compared to older adults. However, the young adults did not see a corresponding improved performance. These results show that results of EEG measures can differentiate sensory-motor integration abilities associated with task complexity and possibly across different groups.

Brain Health, Cognition, and Exercise

Brain health becomes a prominent issue when considering cortical diseases or injuries and age-related declines. Cognitive improvements in healthy populations may act as a preventative measure against neurodegenerative diseases, while cognitive improvements in populations with corresponding neurological disease or injuries and/or age-related declines may limit dysfunction, thus improving the quality of life. Researchers continually explore ways to improve brain health, primarily by altering the structure of cortical neurons and improving cognition and executive functions in healthy individuals (Stillman et al., 2018; Dupuy et al., 2015) and neurological populations (Boots et al., 2015; Vidoni, Honea, Billinger, Swerdlow, &

Burns, 2012). Evidence exists that performing aerobic exercise links to improved grey matter volume (Erickson, Leckie, & Weinstein, 2014) and white matter integrity (Voss et al., 2013) to provide support for using exercise to improve brain health.

Aerobic Exercise Influence on Cortical Activity

Brain imaging is an effective technology when investigating how exercise alters cortical connectivity and functionality. Thus, technologies, which provide information about brain oxygenation changes, connectivity changes, and brain matter/structural alterations, can help make a case for exercise as a possible preventative/rehabilitative treatment option for various individuals, as well as offer insight into how exercise influences brain health. As mentioned previously, brain imaging technologies provide recordings of spatial or temporal aspects of cortical activation and are useful when studying effects of exercise on cortical connectivity and/or functionality.

Spatial Imaging

Spatial imaging measures include various MRI techniques such as fMRI and diffusion tensor imaging, DTI. Remember that fMRI technology can record brain activity/connectivity of different cortical regions during task performances with little head movement and can provide vital information about regions associated with specific task performances. DTI technology allows researchers to observe white/grey matter content within certain brain regions and can provide information about how different lifestyle choices or activities (i.e. physical activity or physical fitness) may influence white or grey matter. Both of these tools provide vital information related to spatial aspects of cortical activation.

fMRI

fMRI literature provides extensive information about how exercise may influence brain activity and connectivity in people of various activity levels. Greater default mode network (DMN) deactivation exists in highly aerobically fit young adult males compared to their sedentary counterparts (Raichlen et al., 2016) and associates with improved executive functions (Raichlen et al., 2016). After an exercise involving walking on a treadmill, overweight and/or obese middle-aged adults (median age of 38.2) present with reduced between network connectivity (Legget et al., 2016) and decreased activity in the DMN (McFadden, Cornier, Melanson, Bechtell, & Tregellas, 2013) compared to similar individuals who did not participate in an exercise intervention. These results suggest that exercise may serve as an effective tool to refine neural circuitry due to fewer, yet more specific formation of connections (Krafft et al., 2014).

Some researchers use exercise as a specific tool to alter diminished brain functioning in various age groups. Researchers show that aerobic exercise classes, i.e. jump rope in overweight/sedentary children, lead to a decreased synchrony between the DMN and brain regions outside of the DMN at rest, a finding which was not observed in overweight/sedentary children who did not participate in activity classes (Krafft et al., 2014). Walking and stretching interventions, which decreased synchrony between the DMN and the frontal executive network during rest, improved synchrony of neural networks within the DMN in older adults (Voss et al., 2010). Whether this synchrony represents greater activation or deactivation remains unclear. Interestingly, non-aerobic stretching evokes DMN functional connectivity changes twice as fast as the aerobic effects of walking which takes twelve months (Voss et al., 2010), likely because

they influence different neural areas. Walking induces more precise connectivity in the frontal executive network, while stretching induces more precise fronto-parietal connectivity (Voss et al., 2010). Occurrence of similar functional connectivity, involving positive correlations in temporal activations between areas within the DMN, were shown to be positively associated with physical markers related to increased physical activity participation (i.e. lower BMI, smaller waist circumference, normal blood pressure, etc.) (Boraxbekk, Salami, Wahlin, & Nyberg, 2016). Aerobic cycling exercise in overweight older adults for 6 months (45 minutes, 2 times a week), can also lead to similar temporal activations between executive control network connectivity and other brain areas (Prehn et al., 2019). Whether the connectivity changes associate with increased fitness levels or simply participating in physical activity remains unclear (Voss et al., 2016).

It seems possible that the functional connectivity between certain cortical regions for neurological populations may vary by aerobic fitness levels and that neurological populations can experience cortical connectivity alterations by increasing fitness levels. Individuals suffering from MCI can improve functional connectivity (increased temporal correlations across frontal, parietal, temporal, and insular lobes) after a twelve-week aerobic exercise intervention program, involving treadmill walking (Chirles et al., 2017). However, little research reveals how aerobic fitness may influence brain connectivity in concussed populations. Researchers show that DMN cortical connectivity in acutely concussed athletes worsens compared to non-athletes with a concussion (Johnson, Dodd, Mayer, Hallett, & Slobounov, 2018). One might argue that the found DMN differences could relate to the number of sub-concussive hits athletes may experience on a regular basis (Johnson et al., 2018). These differences exist in spite of the

possible benefits from increased fitness levels associated with an athletic background. Exploring how increases in $V0_{2max}$ performance may influence these negative alterations in these concussed athletes may be a viable tool for rehabilitation.

DTI

Being physically active appears to improve white matter integrity, as observed in DTI records, compared to non-active individuals, in various age-groups. Overweight children who regularly attend an after school exercise program reveal greater white matter integrity compared to those not exercising (Krafft et al., 2014). Physically active middle-aged adults display greater white matter integrity compared to sedentary controls of similar age (Pasha, Birdsill, Oleson, Haley, & Tanaka, 2018). An exercise intervention involving walking in older adults, improves physical fitness levels, and leads to a greater change in white matter integrity compared to inactive controls (Voss et al., 2013). Improved white matter integrity associates with older adults who have higher aerobic fitness levels and a decreased chance of becoming obese (Marks, Katz, Styner, & Smith, 2011). Greater physical activity levels in older adults also associate with improvements in grey matter integrity (Tian et al., 2014). Clearly, aerobic fitness or physical activity may help preserve or improve brain structure integrity.

Temporal Imaging

Although fNIRS and EEG reveal poor spatial measurement capabilities, they are common cortical imaging measures due to their excellent temporal accuracy. fNIRS technology, which records brain oxygenation levels changes of different cortical regions when performing various tasks, can provide vital information about regions associated with specific task performances, including how strong or weak the oxygenation levels link to task performance. EEG amplitude

intensities change with the temporal changes in task performances. This provides substantial information about how electrical signals can change based on tasks onset and offset. clearly, fNIRS and EEG provide vital information related to temporal aspects of cortical activation.

fNIRS

Certain exercises seems to improve brain oxygenation levels as recorded by fNIRS. Young adults with better performance on a supramaximal Wingate test (an exercise test, completed to exhaustion, that measures anaerobic performance) exhibit greater post exercise prefrontal oxygenation compared to the pre-exercise measurements (Bediz et al., 2016). Prefrontal oxygenation increases were also observed in older women after performing a muscular fatiguing task (Shortz, Pickens, Zheng, & Mehta, 2015). Clearly, greater prefrontal oxygenation can occur in younger and older adults after bouts of more extreme exercise sessions.

EEG

EEG is an effective tool for showing brain activity differences between different types of individuals, among different fitness or physical activity levels, and among age groups. An acute bout of exhaustive aerobic exercise using a cycle ergometer in young adult males leads to increased alpha peak frequency of EEG, which is positively related to arousal and attention (Gutmann et al., 2015). Moderate intensity exercise on a cycle ergometer leads to task-related power decreases in beta band frequency in the contralateral frontal region during performance of a force related motor task (gripping force) (Hubner, Godde, & Voelcker-Rehage, 2018). Decreases in power within this area are positively associated with active/efficient motor processing in young adults (Hubner et al., 2018). Furthermore, acute exercise involving

participating in a 20 minute yoga class may be able to increase theta activity of EEG (Field, Diego, & Hernandez-Reif, 2010), which may link to improved cognition and memory performance (Klimesch, 1999). Exercise, involving resistance training or machine exercises with minimal weight loads, leads to greater centro-parietal P3 amplitudes, an ERP linked to updating specific processes, such as memory and/or context, in healthy young adults (Vonk, Wikkerink, Regan, & Middleton, 2019). Together, these results confirm acute aerobic or resistance exercise and fitness levels link to increased cortical activity as indicated through EEG recordings.

Imaging Conclusions

Evidence exists that exercising and/or fitness level link to improved neuronal function and/or integrity. Researchers also show fronto-parietal brain connectivity differences between young adults who are endurance athletes and healthy, sedentary controls (Raichlen et al., 2016). Aerobically fit younger adults experience improved hippocampal connectivity as well as larger hippocampal volume than sedentary controls (Stillman et al., 2018). They also experience greater prefrontal oxygenation than lower fit individuals (Dupuy et al., 2015). Aerobic exercise also reveals improvements in (Voss et al., 2013) or maintenance of (Burzynska et al., 2014) white matter integrity in older populations, and can increase grey matter volume (Erickson et al., 2014). Therefore, aerobic activity associates with improved cortical activity and connectivity. With identified improvements in cortical neurons known for cognitive and executive functions, we would expect that exercise would also improve performance on certain cognitive measures.

Aerobic Exercise/Fitness Influence on Cognition

Healthy Populations

High levels of physical fitness associate with positive cognitive sensorimotor abilities in healthy populations. Participants between the ages of 18-35 years with a high maximal oxygen uptake (VO_2 max) reveal higher relational memory scores, measured through use of a spatial reconstruction (SR) task, compared to those with a lower VO_2 max (Schwarb et al., 2017). Women of ages 19-34 with a high graded ergometer aerobic fitness reveal shorter reaction times on executive function conditions of a computerized Stroop test than those with a lower aerobic fitness (Dupuy et al., 2015). The Stroop task involves naming the ink color of a visually observed word (i.e. word is blue, but written in green, and therefore the correct response would be green) and/or naming the actual word shown (regardless of the ink color) as fast as possible. Executive functions (i.e. attention, learning/shifting, working memory, and problem solving abilities) of young women with higher aerobic fitness levels exceeded young women with lower fitness levels (Scott, MJ, Koehler, Petkus, & Murray-Kolb, 2016). Young fit adults have greater post-error accuracy corrections than lower fit young adults while completing a flanker task, in which the central target would be either congruent (>>>>> or <<<<<) or incongruent (>><>> or <<><<) (Themanson, Pontifex, & Hillman, 2008). High school males (average age 17.9 years) with a higher VO_2 max achieved faster response times for visual stimuli presented with valid or invalid cues compared to their lower VO_2 max counterparts (Wengaard, Kristoffersen, Harris, & Gundersen, 2017).

Acute exercise also may improve cognitive performance in the short term. Acute bouts of moderate, aerobic exercise on a cycle ergometer reveal improvements for young adults in

Stroop task performance (Yanagisawa et al., 2010), while acute exercise, involving resistance training or low load movement (i.e. exercise machines set to the lowest weight), improves Stroop test response in healthy young adults (Vonk et al., 2019). These cognitive improvements observed short term may lead to cognitive adaptions over time with continued exercise.

Older populations can receive cognitive benefits associated with fitness or physical activity similar to their younger counterparts. Higher levels of aerobic fitness in older adults (average age 63 years) associate with better cognition, by way of reduced reaction times when performing a Stroop test (C. J. Gauthier et al., 2015). Physically active older adults also possess better accuracy compared to sedentary controls when performing a cognitively demanding visuospatial task (Wang & Tsai, 2016). Maintaining greater fitness may also link to improved cognitive abilities associated with performance on The Digital Symbol Substitution Test—DSST in older adults (Edwards & Loprinzi, 2017). The DSST assesses executive functioning, such as visuospatial/motor processing speed and aspects of pairing and free recall. Specifically, participants are asked to draw symbols matched with numbers in a time frame of 2 minutes, each correct drawing and matched symbol results in 1 point (incorrect drawing and matched symbol results in a loss of 1 point) with a maximum total score of 113. People aged 60-85 years with higher aerobic fitness and less sedentary behaviors revealed higher DSST scores than aged-matched comparisons with less aerobic fitness and more sedentary behavior (Edwards & Loprinzi, 2017). Improved executive functioning on the DSST and other cognitive assessments exists for older women (ages 55-72 years) with a higher cardiovascular fitness level, assessed by VO_{2max} levels, than their less fit counterparts (Dupuy et al., 2015). In fact, the aerobically fit older women results compared to the results of the lower fit younger women in the same

study. Moreover, lower fit individuals experience greater cognitive declines, assessed by Stroop test, Trails B , and the Digital symbol test (similar to Symbol Digital Modalities), over the course of 6 years compared to individuals with higher fitness (Barnes, Yaffe, Satariano, & Tager, 2003). Apparently, performing aerobically demanding activities, which result in increased aerobic fitness, may serve as a protective measure against age-related cognitive deficits/declines (Barnes et al., 2003; Newson & Kemps, 2006).

Long-term exercise interventions can produce cognitive improvements in the healthy elderly populations. Older adults enrolled in a walking program which involved walking 3 times a week for 40 minutes for an entire year show improvement in cognitive functions related to short term memory (Voss et al., 2013). Older adults enrolled in other aerobic exercise interventions (treadmills, stationary cycles, stepping machines, ellipticals, etc.) for 25-30 minutes, three times a week for a total of 10 months improve their performance on a Stroop Task (Smiley-Oyen, Lowry, Francois, Kohut, & Ekkekakis, 2008). A three month multicomponent fitness intervention involving agility, strengthening, stretching, balance, cognitive training (such as reversing a learned order of sequential movement/exercises), obstacle avoidance while walking, and resistance training lasting for 1 hour, twice a week can improve aspects of cognitive functions in older adults (Forte et al., 2013). Cognitive functions included speed of task completion, visual attention, and cognitive flexibility/ability to switch attention to complete a task (Trails B) (Forte et al., 2013). Marmeleira et al. 2018 show that 60 minute sessions, twice a week for 8 weeks which included aerobic, strength, balance/agility, flexibility, and cognitive training lead to improvements in multiple physical fitness measures involving lower body strength (assessed by 30s chair stand test), and aerobic endurance (assessed using

the 6 minute walk test, a measured distance traveled after walking for 6 minutes). The same study also reports improvements in cognitive measures related to selective/sustained attention using d2 test (which involves correctly selecting a “d” surrounded by two marks (i.e. ‘d’), motor speed/visuospatial ability using the trail making test, and simple visual reaction time. Cognitive training incorporated dual task training, visual attention training, which is assessed by success of finding and pointing to an object, and working memory training assessed by memorizing a sequence of movements (Marmeleira, Galhardas, & Raimundo, 2018). Ward et al. 2017 also show improvements to cognition (i.e. visuospatial reasoning assessed by the Irrigator game, and task switching assessed using the Pen Emu P game) as a result of a multimodal program that included stretching, aerobic, resistance, and cognitive training for 28 sessions over 4 months (Ward et al., 2017). Cognitive training included playing computerized games designed to improve executive functions through improved visuospatial reasoning and improved task switching, and transcranial stimulation. However, these games (Irrigator and Pen EMU P) are not well defined within literature. As a result, it is difficult to substantiate their validity. While cognitive training may help improve cognitive functions when used in conjunction with exercise programs, it is also evident from the literature that exercise alone can improve cognition. Although some researchers suggest that cognitive improvements may result from increased activity levels regardless of improved aerobic fitness (Smiley-Oyen et al., 2008), others suggest improved aerobic fitness may explain the cognitive improvements (Dupuy et al., 2015).

It appears that acute exercise may also positively affect cognitive performance. Hogan et al. 2015 show error rate differences exist between high and low fit adolescents when comparing reaction times for Go/No-Go tasks. However, these differences disappeared after a

20-minute acute bout of aerobic exercise, with the unfit group improving their performance (Hogan et al., 2015). Loprinzi & Kane 2015 show increased cognitive functioning (i.e. improved concentration assessed using a Feature Match test, which involves identifying whether two boxes contain similar or different objects) after a 30-minute acute bout of exercise in healthy young adults regardless of fitness levels (Loprinzi & Kane, 2015). Gmiat et al. 2017 show improvements to concentration and spatial memory, as assessed by the CORSI Block Tapping Test, and to arithmetic distraction, assessed by the Grid exercise test in young women after an acute 30-minute bout of exercise involving high-intensity, body weight circuit training. Middle-aged women reveal no cognitive improvements after participating in the same 30 minute exercise bout (Gmiat et al., 2017). Also, Bediz et al. 2016 show no cognitive differences exist between individuals who perform well or poorly on a supramaximal anaerobic Wingate test (using a cycle ergometer) when completing a 2-back test (a cognitive test of response time to pressing a button when a letter on a screen matches the letter presented on the same screen two steps earlier) before or after exercise (Bediz et al., 2016). Thus anaerobic exercise may not be associated with better cognitive performance. These studies indicate that acute bouts of aerobic activities can play a role in improved cognitive function in adolescents and young adults. Further studies could be used to determine if middle and older adults can reap the same benefits.

Neurological Populations

Participating in aerobic fitness training and increasing an individual's aerobic capacity can produce cognitive benefits in certain neurological populations. Increases in VO_2 max associate with improvements in mental speed and attention for individuals diagnosed with

Alzheimer's disease (Sobol et al., 2018). Multicomponent exercise including 20-30 minutes of aerobic training, resistance training, and sports participation once a week for 6 months, can improve episodic memory for individuals diagnosed with Alzheimer's induced amnestic mild cognitive impairment (Teixeira et al., 2018). Furthermore, withdrawal from exercise for this same population can result in cognitive declines over the 6 months. Boots et al. 2015 reveal that people at risk for Alzheimer's disease with high fitness levels show significant improvements in cognitive measures associated with learning, memory, and mental speed/flexibility compared to those with lower fitness levels (Boots et al., 2015). Similar improvements in cognition are observable in individuals with Multiple Sclerosis (Sandroff et al., 2016), Parkinson's Disease (Duchesne et al., 2015), and individuals suffering from mild cognitive impairments (Baker et al., 2010; J. C. Smith et al., 2013) after participating in various types of aerobic exercise. Clearly, neurological populations at risk for cortical declines can experience improved cognitive functioning through various types of exercise interventions.

Some positive aerobic exercise influences on cognitive function in individuals with a history of brain injury also exist. Individuals at least post 6 months from a Traumatic Brain Injury can improve speed of information processing assessed using the Trail B after a 12 week treadmill training intervention (30 minute sessions, 3 times a week) (Chin, Keyser, Dsurney, & Chan, 2015). Results from a recent meta-analysis revealed that people with a history of concussion(s) participating in various types of short-term aerobic exercise, including running, cycling, and stretching, may also help improve visual memory and reaction time assessed using immediate post-concussion assessment and cognitive testing (ImPACT) (Lal, Kolakowsky-Hayner, Ghajar, & Balamane, 2018). The reduction of post-concussion symptoms were also

observed, characterized as an improved post-concussion symptom score (PCSS), which is affected by number and duration of symptoms. Aerobic activity may improve cognitive function in people with brain damage due to injury. Less is known about the potential effects of exercise and aerobic activity on cognitive-motor and sensorimotor control in the concussed population.

Aerobic Exercise/Fitness Influence on Neurons and Cognition

Assessing cognitive function and brain activity during or after exercise or in people of different fitness levels offer insight into the brain activity changes which direct cognitive improvements associated with exercise and/or fitness. Acute bouts of moderate exercise, involving aerobic exercise on a cycle ergometer, increases prefrontal oxygenation levels during improved Stroop task performance in young adults (Yanagisawa et al., 2010). Acute bouts of exercise on a treadmill also leads to increased P3 amplitude while completing a flanker task with decreased response times after exercise completion, compared to the rest condition (O'Leary, Pontifex, Scudder, Brown, & Hillman, 2011). Exercise involving resistance training or low load movement improves Stroop test response times and leads to greater centro-parietal P3 amplitudes in healthy young adults (Vonk et al., 2019). Tsai et al. 2014 show that highly fit young adults participating in an acute bout of aerobic exercise on a treadmill 30 minutes before EEG recordings reveal greater P3 amplitudes, while performing a visuospatial attention task, than low fit individuals participating in the same bout of exercise as well as fit individuals not participating in the acute bout of exercise (Tsai et al., 2014). Tsai et al. 2016 suggests that improvements in both switching cost (improved performance on a task-switching paradigm) and neurophysiological benefits (increased P3 amplitudes) after acute aerobic exercise may only be available to young adults with a high aerobic fitness level (Tsai, Pan, Chen, Wang, &

Chou, 2016). This is because lower fit individuals had improved task switching (but still had a larger switching cost than higher fit individuals) and no P3 amplitude changes after acute exercise. Acute bouts of exercise may lead to improved neurophysiological capabilities, which my lead to improved cognition.

Higher fitness levels associated with better cognitive performance (a composite score derived from for cognitive tests including: Reaction time test, Stroop test, Symbol Digital Modalities involving a key code where numbers are assigned a random symbol and participants have to fill in a blank space below a symbol with a corresponding number or vice versa, and Trails B assessment involving drawing a line connecting alternating numbers and letters, e.g. 1-A-2-B-3-C-4-D) than lower fitness levels in young adults (Dustman et al., 1990). While acute exercise alone influences cortical activity, fitness level also seems to play a role in activity of ERP. Visual stimulation involving lights flashing at different intensities produced shorter ERP latencies in these same young adults (Dustman et al., 1990). Clearly, healthy teenagers and young adults receive neurological benefits from improved aerobic fitness, which could lead to better maintenance of their neurological health as they age. Highly fit individuals (with a high VO_2 max) also reveal fewer errors and a greater ERP, while performing a flanker task, which may be associated with their improved performance on this task compared to lower fit individuals (Themanson et al., 2008). Different beta phase synchronization and improved performance exists in higher fit young adults compared to lower fit young adults when completing the incongruent portion of a Stroop task (Wang et al., 2019). The greater beta synchronization, defined as increased beta amplitude, observed in incongruent tasks by higher fit individuals may mean better top-down control of attention, which may be related to

improved cognition (Wang et al., 2019). Highly fit younger adults may have improved neurophysiology leading to improved cognitive functioning.

Highly aerobically fit young and older women also revealed greater prefrontal oxygenation and improved task performance compared to their lower fit counterparts during the Stoop task (Dupuy et al., 2015). While performance of a memory learning task is similar between high and low fit adolescents, the highly fit individuals reveal greater deactivations in the default mode network (DMN) areas (highly integrated brain areas that can include hippocampus, inferior parietal lobe, medial prefrontal cortex, and posterior cingulate cortex), compared to the low fitness group (Herting & Nagel, 2013). Physically active older adults have greater P3 amplitudes when performing a cognitively demanding visuospatial task, which resulted in better accuracy compared to the sedentary individuals in the control group (Wang & Tsai, 2016). Li et al. 2014 show that after older adults participating in cognitive training, Tai chi, and group counseling (sessions involved discussing positive experiences and the meaning of life), connectivity between the prefrontal cortex and temporal lobe increases (Li et al., 2014). Moreover, aerobic fitness levels associate well with white matter integrity and executive function performance in individuals with MCI (Ding et al., 2018). Changes to neurophysiology associated with improved fitness, may also lead to improved cognitive functioning in aging and special populations.

It also appears that the type of exercise task can influence cognition differently, but not neural activity (Tsai, Pan, Chen, & Tseng, 2017). Performing open skilled exercise tasks associated with an unpredictable environment, like Table Tennis, leads to improved reaction times during a task-switching paradigm compared to closed skill exercise tasks associated with

a relatively stable or predictable environment, as in jogging. However, performance of table tennis drills and cycling/walking (for 30 minutes) lead to increased EPRs (increased P3 amplitudes) and are linked to updating specific cognitive processes, such as memory and/or context, during a task-switching task (Tsai et al., 2017). Thus, although open skilled exercises lead to improved reaction times during a task-switching paradigm, both open and closed skilled exercises lead to increased cortical activation. It could be beneficial to use both open and closed skilled exercises in populations with cognitive and/or neural deficits.

Physiological Mechanism Supporting Neurological Changes Due to Exercise

The neuronal changes observed in individuals associated with high aerobic fitness may result from a physiological mechanism. Multiple explanations exist for the possible physiological mechanism(s) underlying the neuronal changes with exercise. These changes may result from either short-term or long-term effects that are induced by increasing physical activity levels (Stimpson, Davison, & Javadi, 2018).

Short-Term Effects

Acute bouts of cycling can lead to greater neural activity in parietal cortices, hippocampal areas, and cerebellum areas. (e.g., (Chen, Zhu, Yan, & Yin, 2016)). Acute bouts of exercise have led to an increase in brain blood flow/oxygenation, catecholamines (i.e. norepinephrine, epinephrine, and dopamine), cortisol, serotonin, neurotrophins (and myokines. It is unclear to what degree each of the aforementioned aspects lead to improved cognition, but all have been associated with improvements to executive functioning (Moriarty et al., 2019). Lactate production, associated with exercise, could also lead to improved memory

processing through the production of glutamate (one of the main energy sources used by the brain) (Basso & Suzuki, 2017), or vice versa.

Long-Term Effects

Long-term effects of aerobic exercise/physical activity can result in physiological changes, and therefore influence the brain's ability to change (Stimpson et al., 2018). Long-term aerobic exercise, involving treadmill running in rats, leads to significant increase in angiogenesis (Slopack et al., 2014). Increased brain oxygenation could directly result from increased angiogenesis, which is known to increase levels of neurotrophins (i.e. brain-derived neurotrophic factor (BDNF) and vascular endothelial growth factor (VEGF)). Increases in BDNF (Brunelli et al., 2012; Dinoff, Herrmann, Swardfager, & Lanctot, 2017; Morais et al., 2018); and VEGF (Schobersberger et al., 2000) may relate to improvements in cognition (Stimpson et al., 2018). Eventually, neural structural/functional adaptations will occur due to this increased oxygenation and increased neurotrophins (Stimpson et al., 2018). Specifically, increased angiogenesis may be the mechanism responsible for the increased oxygenation, and therefore, the long-term neuronal changes, which may relate to improved cognition (Stimpson et al., 2018).

Mechanism Conclusions

Aerobic exercise leads to physiological processes related to cortical activity (i.e. increased oxygenation) and the brain's adaptability (i.e. neural plasticity). The processes and/or mechanisms provide a rational for how aerobic exercise may improve cognitive performance or cortical activity during cognitively demanding tasks. Continuing to investigate how these

changes result from exercise may help structure better rehabilitation or preventative measures against neurodegeneration in at risk or neurological populations.

Literature Gaps

The use of coupled verses decoupled eye-hand movements in CMI research is becoming a prominent research technique and provides useful information about cognitive-motor and sensorimotor differences between neurologically healthy and unhealthy populations. Initial findings in the area are promising as they offer insight assessment of neurological declines. However, multiple gaps in literature associated with CMI research and, in general, cognitive-sensorimotor research exist. Addressing these gaps could lead to future research in hopes of identifying ways to improve assessments and/or better understand strategies used to avoid or correct neurological declines. The following text presents information on some of the literature gaps within the CMI literature with these improvements in mind.

Eye Movements Role

Current literature lacks certain considerations that could influence the future of CMI research. The poor performances observed from the eye-hand decoupling tasks in CMI research for healthy individuals may result from difficulties due to the increased need to control greater degrees of freedom associated with eye-hand separation in this task, and/or because a cognitive rule must be implemented to perform the correct motor action (Dalecki, Gorbet, & Sergio, 2019). As mentioned previously, eye movement type can change or influence body movements (Yeomans et al., 2018), including those of the hands (Engel & Soechting, 2003). Since CMI research is limited in regards to eye movement control selection during task performances, use of varied eye movements could explain differences in task performance for

various people (Engel & Soechting, 2003). Thus, future research needs to take into consideration how these eye movements influence eye-hand decoupling tasks to whether greater impairments between hand and eye movement decoupling exist when using specific eye movements.

Postural Changes

Eye-hand coupling and decoupling tasks may depend on constraints and/or posture control. Researchers show that pointing errors observed during more constrained seated positions may disappear when similar tasks are performed while standing upright and less constrained (Hondzinski & Kwon, 2009). Similar results may be observed during the CMI tasks, yet none currently exist. Changing posture from sitting to standing may also degrade eye-hand coordination tasks, such that the difference may only be exaggerated in people with poor postural control while standing and performing eye-hand coordination tasks. Neurological populations, which exhibit increased sway during standing balance, may experience altered balance while performing standing CMI tasks. The potential exists that the altered balance could influence coupled and decoupled CMI task performance or that the altered CMI task performance couple alter an individual's postural control. Investigating how healthy populations postural control varies during these CMI tasks will build a foundation to investigate other people with postural control declines during CMI tasks.

Sedentary Populations Sensorimotor Cognitive Integration

CMI tasks may provide greater sensitivity to neurological changes than simple cognitive-motor measures alone (i.e. Stroop test). As state previously, evidence suggests that higher levels of aerobic fitness can positively influence these simple cognitive-motor tasks. To our

knowledge, studies about the effects of fitness level on performance during CMI decoupling tasks do not exist, yet could ultimately provide insight into neurological decline and/or recovery as well as cognitive-motor/sensorimotor control. Therefore, future research should include experiments which determine whether fitness levels do influence CMI performance outcomes. If differences exist, and correspond to level of aerobic fitness, then the positive influence of exercise could lead to rehabilitation efforts for the cortical declines also diagnosed by CMI assessment.

CHAPTER 3. EYE MOVEMENTS INFLUENCE ON COUPLED AND DECOUPLED EYE-HAND COORDINATION TASKS: STUDY 1

Introduction

Performance of goal-directed visuomotor skills rely heavily on the coordination of the hand and eyes. Although people can alter how they move to integrate control of the hand and eyes for visually guided movements, task requirements and complexity can direct the integration of neural control (Crawford, Medendorp, & Marotta, 2004). Additionally, humans can use smooth pursuit eye movements to successfully track their hand without any visual information, as in a dark environment (G. M. Gauthier & Hofferer, 1976), revealing a strong link between movement of the hand and eyes, even without visual inputs. Furthermore, use of visual and proprioceptive information improves spatial accuracy compared to the use of purely proprioceptive cues with no visual feedback, emphasizing the importance of visual information in the spatial realm (Ren et al., 2006). While the eyes and hand are normally coupled during reaching movements, the two can also be separated, or decoupled, to perform a precise reaching task, at least if visual input remains available (Foerster, 2016).

Multiple variations of eye-hand coupling/decoupling tasks exist in the literature. Increasing cognitive demands of the task, such as decoupling the eyes and hand such that they move to distinct spatial directions, moving to remembered targets (Brown et al., 2015; Salek et al., 2011), or performing horizontal plane movements while viewing vertical plane presentations (Brown et al., 2015; Hawkins & Sergio, 2014; Salek et al., 2011), corresponded to slower reaction and movement times and worse trajectory patterns towards the endpoints. As expected, cortical activity also differs for coupled and decoupled eye-hand coordination tasks.

Decoupling of the hand and eyes resulted in greater parietal and cerebellum activity compared to coupled movements (Gorbet & Sergio, 2016) to suggest altered brain activation patterns during tasks where the eyes and hand move either to the same or to distinct locations.

While coupling and decoupling tasks require visuomotor mapping and a cognitive rule to execute the correct motor action (Gorbet & Sergio, 2016), it is important to notice that the type of eye movement used is often ignored (Brown et al., 2015; Dalecki et al., 2016), yet could influence performances (Gorbet & Sergio, 2009). Naturally, humans tend to saccade to the target such that the eyes 'lead' the hand to guide its movement (Angel et al., 1970). Electromyography (EMG) onset of the reaching limb actually precedes initiation of saccadic eye movements to suggest preprogramming of the limb, before movement initiation for coupled eye-hand movements (Gribble et al., 2002). Whether saccades remain common for decoupled eye-hand movements, warrants exploration if differences exist between eye movement conditions during eye-hand coupling/decoupling task performances.

A combination of saccades and smooth pursuit eye movements can be used during performance of coupled goal-directed reaching tasks (Engel & Soechting, 2003). People use saccades, known for their high maximum speeds (Bahill, Clark, & Stark, 1975) and long latencies (Fuchs, 1967), to quickly reposition the eyes for sudden changes in target movement direction during visual tracking tasks using smooth pursuit eye movements. Relative to saccades, smooth pursuit eye movements are known for their slower speeds (Fuchs, 1967) and shorter latencies (Erkelens, 2006). Coupling the eyes and hand together decreased hand latency and increased latency of the eyes compared to tracking a moving target using only the hand with eye fixation or using saccadic/smooth pursuit eye movements with hand fixation, respectively (Engel &

Soechting, 2003). Coupling the eyes and hand when reaching toward a moving target allowed for greater speed of saccadic eye movements than decoupling the movements (Snyder et al., 2002). Although eye movements were not recorded, coupling the eyes and hand when reaching toward a stationary target allowed for greater speed of hand movements than decoupling the movements (Dalecki et al., 2016; Dalecki, Gorbet, & Sergio, 2019; Salek et al., 2011), the former of which could also improve endpoint spatial accuracy of the hand (Salek et al., 2011). Improvements in hand spatial accuracy also accompanied coupling of the eyes and hand during reaching tasks compared to decoupling with eye fixation eccentric to target location (Henriques, Klier, Smith, Lowy, & Crawford, 1998; Vercher, Magenes, Prablanc, & Gauthier, 1994). Better spatial accuracy was expected with eye-hand coupling due to less separation of the hand and eye at movement termination (Salek et al., 2011). Comparing temporal and spatial aspects of coupled and decoupled eye-hand coordination performances using smooth pursuit, saccades, and fixations would offer greater insight into eye movement influences over task performances.

The aim of the present study was, therefore, to investigate whether various type of eye movements influence temporal and spatial characteristics of hand movements during coupled and decoupled visuomotor tasks. We included smooth pursuit or saccadic eye movements during coupled visuomotor task conditions, and added fixations during decoupled visuomotor task conditions. Coupled movements in the present study refer to the hand and eyes moving towards the same end target, whereas decoupled movements refer to the eyes and hand not moving towards the same end target. Decoupled movements included oppositely directed movements of the hand and eyes or centralized stabilization of eyes during hand movement.

We aimed to shed light on whether eye movements could contribute to performance differences during coupled and decoupled visuomotor tasks. Based on known eye and hand movement characteristics, we hypothesized that saccadic eye movements would result in slower responses and faster movements of the hand compared to smooth pursuit and fixations. We also expected that smooth pursuit eye movements, in which stronger eye-hand coupling occurs with slower tracking (Huang & Hwang, 2013), would result in slower hand movements compared to fixations and that the greatest spatial accuracy would depend on location of the eyes.

Methods

Participants

Twenty-four young adults (*M* = 21 years and *STD* = 1.1; 15 females), recruited from Louisiana State University, participated in this study and provided written consent prior to participation. Participants reported writing and drawing with their right hand and achieved >40 on the Edinburgh handedness exam (Oldfield, 1971). They had no difficulties viewing targets with visual acuity 20/40 or better, the acuity needed to read road signs and make adequate driving decisions (Owsley & McGwin, 2010), and reported no history of concussion, diabetes, neuromuscular disease, cardiovascular diseases, or orthopedic diseases.

The two groups of participants included group Smooth Pursuit (SmP) and group Saccade (SAC). Groups received different instructions linked to participant's eye movement during the eye-hand coordination task.

Procedures

Participants sat in a chair located a comfortable distance in front of a laptop wearing a black, cloth glove on their right hand. The head and upper body were not restricted. During the task, a vertical touchscreen laptop computer (15.6-inch Dell Inspiron 5000; resolution 1920 x 1080 pixel) was used for data collection and to record finger movements. A central yellow target of 20 mm diameter in the middle of the screen provided the location of start position. Peripheral red circles of 20 mm diameter, located up, down, left, and right at a center-to-center distance of 75 mm from the central target, provided end target locations for the cursor movement. Targets were presented on a 170 x 170 mm black background with colored grey surround to maintain a constant visual border. For fixation trials (see details below), a 20 mm sticky dot (with a 10 mm diameter hollowed center) was placed at the central target location on the screen to provide a focal point. Participants were instructed to start with their right index finger at the middle of the central target (start position) and to move a cursor to the center of a peripheral target, when it appeared on the screen, as quickly and as accurately as possible.

Movements were made under five different conditions involving various coupling and decoupling of the eyes, hand, and cursor. Cursor movement was always linked to movement of the finger on the touchscreen. In condition EH, eyes and hand/cursor moved toward the target, thus were coupled. Sliding the finger on the vertical touchscreen moved the cursor from the central target to a peripheral target (Figure 3.1a). In condition FH, participants maintained fixation of their eyes on the central target, while they slid the finger as described in condition EH (Figure 3.1a). In condition EFR, while participants maintained fixation of their eyes on the central target, they moved the cursor toward the target with an oppositely directed finger

movement, i.e., the cursor feedback was reversed 180 degrees (Figure 3.1a). In condition EHR, participant's eyes moved toward the peripheral target with the cursor which moved toward the peripheral target with oppositely directed finger movements as in EFR (Figure 3.1a). In condition ERHR, the cursor moved toward the target with oppositely directed movement of the finger and eyes (Figure 3.1a). After each trial, participants held their finger in place until the center target reappeared, then slid it back to the central target and prepared for the next trial.

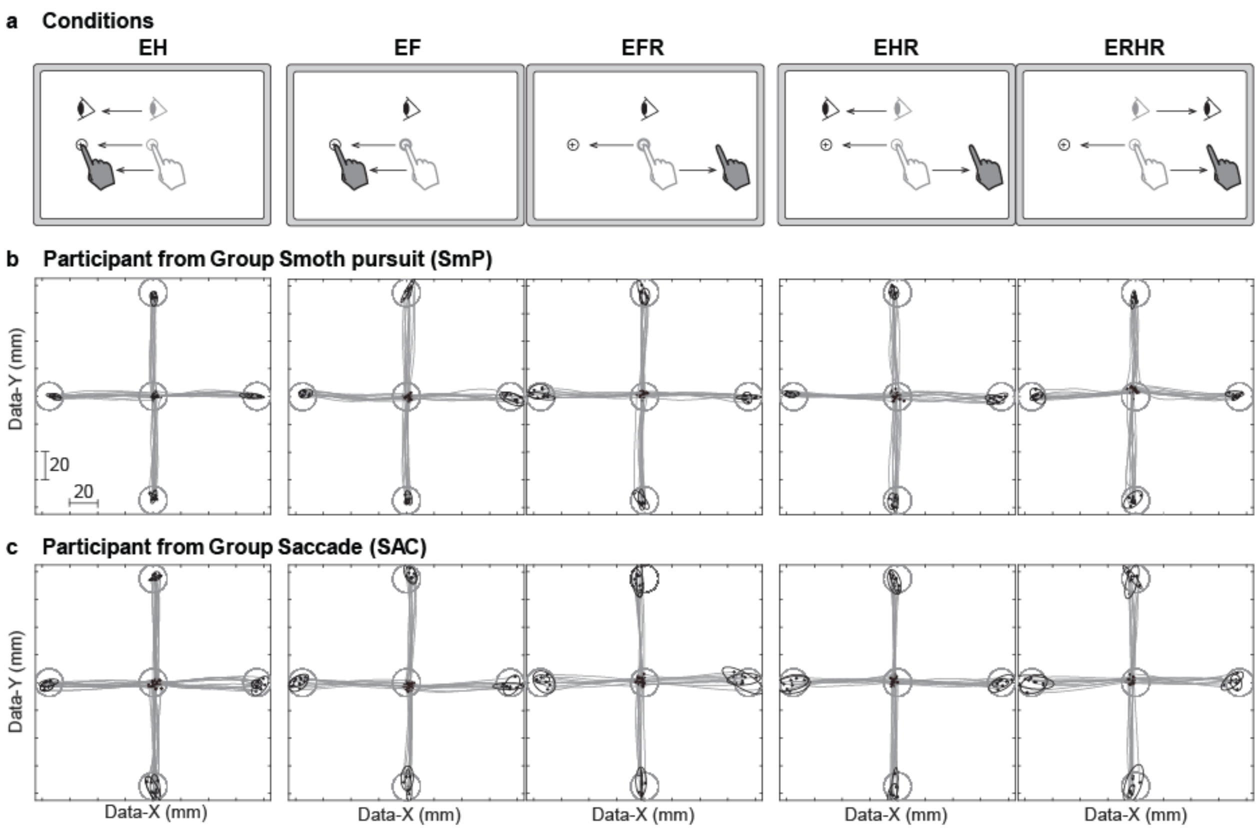


Figure 3.1. Visual representation of the 5 task conditions. **a)** EH (eyes and hand moved to target), FH (eyes fixated on the screen center, and hand moved to target), FHR (eyes fixated on the screen center, and hand moved away from the peripheral target), EHR (eyes moved to the peripheral target, and the hand away from the peripheral target), and ERHR (eyes and hand moved away from the peripheral target). The home target was in the screen center, represented in the figure by a circular target (in condition EH/EHR/ERHR/FH/FHR).
(caption cont.'d.)

Darker grey eye and hand symbols denote the instructed eye and hand movement direction. Peripheral circles denote a reach target. The dark cross denotes the cursor feedback given to participants, and the grey lines represent the movement direction for hand movement. **b)** shows exemplary data plots of all trials of each condition from one participant of group 'Smooth pursuit', and from one participant of group 'Saccade' (**c**). Note that spatial movement trajectories (represented by the grey lines) look very similar between both participants but movement endpoints (represented by the grey dots) seem to be a bit further away from the peripheral target center for participant SAC compared to the participant from group SmP.

Instructions to participants varied between groups. Group SmP was instructed to use smooth pursuit eye movements to follow their finger movements during EH and ERHR conditions and to follow the cursor during the EHR condition. Group SAC was instructed to saccade the eyes to the peripheral target in the EH and EHR conditions and to the estimated ending finger position in the ERHR condition. Instructions for both groups (SmP and SAC) were the same in condition EF and EFR; to fixate on the central target.

Participants performed 16 practice trials (4 in each direction; left/right and up/down) prior to each condition. After practice within a given condition, participants performed two rounds of 20 trials (i.e., 40 trials with 10 trials in each direction per condition). If participants did not stop in the target (i.e., continued through the target), an additional trial was added. A total of 200 trials were available after data collection for each subject before the removal of incorrect trials due to incorrect eye-movements (see below). Cursor movements directed by finger movement on the touchscreen were collected using a customized application and recorded at 60 Hz (BrDI™). A mobile eye tracker was used to record gaze position movements on the touchscreen at 60 Hz to ensure instructions were followed (SMI, Teltow, Germany). Calibration of gaze position was achieved by performing a three point fixation calibration using manufacture guidelines. An investigator viewed gaze positioning prior to and during the

experiment trials to help ensure its accuracy. Gaze position was reset to the start position between rounds when needed.

Data Analysis

For the eye movements, frame-by-frame offline review of gaze video and position data using BeGaze software (SMI, Teltow, Germany) helped determined whether correct eye movements were performed. Incorrect trials (performing the wrong eye movement, i.e., saccading to a target when they should be fixating on a central target, or moving the hand in the wrong direction, i.e., reversal error or moving straight through a target) were removed from data analyses.

For the hand movements, the x and y coordinates of the cursor position were recorded during each trial. Remember that the cursor position was controlled by the finger movement. Raw position data were converted into MATLAB readable format using a custom written C++ application. Individual movement paths derived from the cursor location were first low-pass Butterworth filtered at 10Hz (Matlab, Mathworks Inc.). Trials were deemed incorrect and removed from analyses, if reaction time was too short (< 150 ms). A customized MATLAB program was then used to calculate spatial and temporal variables. The software detected the initiation and end of a movement at 10% of peak velocity similar to elsewhere (Dalecki, Gorbet, & Sergio, 2019). Movement start and end of each trial were inspected by an experienced analyzer. If the program labeled them incorrectly or was not able to detect the start or end automatically, the analyzer provided a frame where it could define the correct start and or end in accordance with the 10% threshold.

Trial removal left us with at least 23 trials for each condition and participant. Variables of interest included temporal variables (reaction time—RT, movement time—MT, response time—RespT, and peak velocity—PV) and spatial variables (absolute initial direction error—aIDE, path length—PL, and absolute endpoint error—AE). For the temporal measures, RT (milliseconds; ms) was defined as the time interval between target presentation and cursor movement onset. MT (ms) was defined as the time interval between movement onset and end. RespT (ms) was movement time plus reaction time. PV (mm/s) was defined as the cursor's peak velocity during movement. For the spatial variables, aIDE (°) was defined as the angle between cursor position at movement onset and at 100 ms after movement onset in relation to the straight line between the centers of the central and peripheral target circles. PL (mm) was defined as the trajectory path between movement onset and end. AE (mm) was defined as absolute distance between cursor endpoint and target center.

Statistical Analysis

An independent *t* test was used to ensure that age of participants was similar between groups. Data were checked for normal distribution and sphericity, using a Shapiro-Wilk's test and Mauchly's test, respectively. A mixed repeated measures ANOVA with the within-subjects factor Condition (EH, EF, EFR, EHR, ERHR) and between subjects factor of Group (SmP, SAC) was used to determine whether each variable of each experiment differed across conditions and group, for normally distributed data. Data were corrected using Greenhouse-Geisser when violations of sphericity occurred. Tukey's HSD post-hoc tests were used when appropriate. Non-normal data were transformed using $\log_{10}$. Non-parametric statistics were used for non-normal distributions with unsuccessful transformations. Use of Man-Whitney U Tests with Bonferroni

corrections indicated between group differences. Friedman ANOVAs and Wilcoxon matched-pair tests with Bonferroni corrections were used to identify condition differences within each group. Statistical significance prior to corrections was set at the standard p-value of 0.05. Statistica software was used for analyses (Version 25).

Results

Twelve Group SmP participants (*M* = 21.2 years and *STD* = 0.94) included 9 females and revealed a similar age range to the 12 Group SAC participants (*M* = 20.9 years and *STD* = 1.3) with 7 females ($t(22) = 0.56$). Results of parametric analyses on normally distributed original and transformed (aIDE) data are provided in Table 3.1, while results of non-parametric analyses non-normally distributed data are provided below. Figure 3.1b shows examples of typical movement trajectories of one participant from each group for the five conditions. Note that the movement trajectories look very similar between participants and across conditions; however, endpoint locations can vary.

Table 3.1. Results for normally distributed variables

Variable	Effect	F-value	df	*P*-value	Effect size
aIDE	Group	1.28	(1,22)	0.27	0.05
	Condition	3.12	(4,88)	0.02*	0.12
	Group x Condition	3.39	(4,88)	0.01*	0.13
AE	Group	11.64	(1,22)	0.003*	0.35
	Condition	20.35	(4,88)	<.0001*	0.48
	Group x Condition	0.46	(4,88)	0.77	0.02
PL	Group	0.10	(1,22)	0.72	0.01
	Condition	3.10	(2.6,57.2)	0.04*	0.12
	Group x Condition	0.30	(2.6,57.2)	0.81	0.01
MT	Group	43.57	(1,22)	<.0001*	0.66
	Condition	55.96	(4,88)	<.0001*	0.72
	Group x Condition	28.94	(4,88)	<.0001*	0.57
PV	Group	29.83	(1,22)	<.0001*	0.58
	Condition	31.14	(2.23,49.08)	<.0001*	0.59
	Group x Condition	23.42	(2.23,49.08)	<.0001*	0.41
RespT	Group	40.35	(1,22)	<.0001*	0.65
	Condition	50.19	(4,88)	<.0001*	0.70
	Group x Condition	23.42	(4,88)	<.0001*	0.52

Note: *significant effect at alpha < .05

Plots of Group x Condition interactions are presented in Figure 3.2, with spatial measures aIDE (a), AE(c), PL e) presented in left panels and temporal measures RT (b), MT (d), and PV (f) presented in right panels. Main effects of Group were limited to AE (Figure 3.2c) for spatial variables. The greater AE for group SAC than group SmP suggested a greater overall accuracy for participants in the SmP group. Results also revealed Condition effects for AE to indicate it was smaller for EH compared to all other conditions, and that AE for EF was smaller than ERHR. Thus, coupling the eyes and hand while moving toward the target produced the greatest endpoint accuracy, but fixation decoupling produced an endpoint advantage over coupling of the eyes and hand moving away from the target. Groups produced similar aIDE (Figure 3.2a), but a Condition effect revealed that aIDE was greater for EH compared to EF and indicated a slight initial direction advantage when hand movement toward the target

accompanied fixation. When adjusting for Group in the interaction, EHR exceeded EF for aIDE only for group SmP to suggest an initial direction error advantage for decoupled movements involving fixation and hand movements toward the target compared to reversal hand movements using smooth pursuit. Groups also produced similar PL but a condition effect revealed that EF and ERHR were greater than that of EHR (Figure 3.2e). Clearly, initial direction of movement and the distance moved do not benefit from the use of saccades or smooth pursuit. Furthermore, a 180 degree movement separation of the eyes and hand led to the shortest average trajectories.

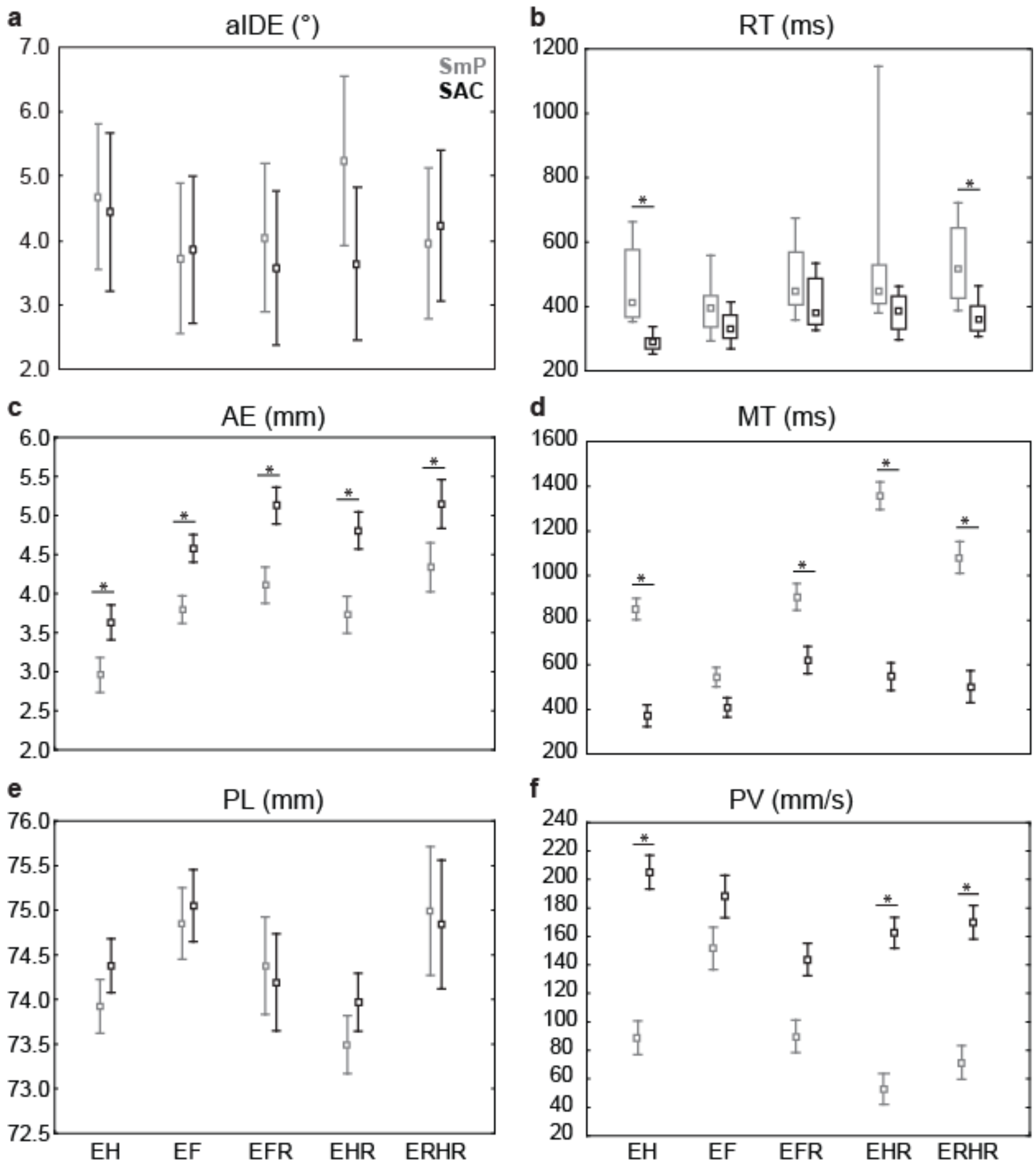


Figure 3.2. Plots of hand data. Plots of **a)** mean reaction time (RT), **b)** median absolute initial direction error (absIDE), **c)** mean movement time (MT), **d)** mean absolute error (AE), **e)** mean peak velocity (PV), and **f)** mean path length (PL) of group 'Smooth Pursuit-SmP' (grey color) and group 'Saccade-SAC' (black color) across the five conditions. Temporal variables are shown in right columns with spatial variables in the left column.
(caption cont.'d.)

* = *P* < .05. Error bars represent 95% confidence interval (a), standard errors (c-f), or minimum to maximum values with a 25%-75% box value range (b).

Significant Condition x Group differences existed for all temporal variables. When temporal variables differed by Condition, EH and EF revealed shorter times and faster speeds than the remaining conditions. When temporal variables differed by Group, group SAC revealed shorter times and faster speeds than group SmP, especially during conditions in which the eyes and hand were coupled (EH and ERHR, Figures 3.2b, 3.2d, and 3.2f) and/or hand reversal existed (EHR and ERHR, Figures 3.2d and 3.2f). These data show that time to react using saccadic eye movements exceeded those using smooth pursuit, and that using saccadic eye movements resulted in faster movements than using smooth pursuit. Group SmP produced shorter RT for EF compared to EFR and ERHR and while group SAC also produced shorter RT for EF compared to EFR, they produced the shortest RT for EH (Figures 3.2b). These results suggest that use of saccadic eye movements for coupled movements toward targets improved reaction capabilities compared to fixations. MT Group differences were most surprising for EFR, a fixation condition performed by both groups (Figures 3.2c). Group SmP produced MT (Figures 3.2d), RespT (data not shown), and PV (Figures 3.2f) differences revealing the shortest times and fastest speeds for EF with similar times and speeds for EH and EFR, while the greatest MT existed for EHR and the greatest RespT and smallest PV existed for EHR and ERHR. In contrast, similarities existed between EH and EF times and speeds and among EFR, EHR, and ERHR times and speeds for group SAC. Although group SAC produced shortest times and fastest speeds in EH and EF compared to EFR, only shorter times and/or faster speeds existed for EH compared to EHR (MT, Figures 3.2d) and ERHR (RespT and PV, Figures 3.2f). Together, these data suggest the following in regards to temporal measures. First, using fixations decreased MT and RespT and increased

peak speed compared to using smooth pursuit eye movements, whether performing hand movements directly toward the targets or using hand reversal. Second, moving the hand directly toward targets, especially during movement coupling using saccades, produced the shortest reaction, movement, and response times and greatest peak speeds compared to movements using hand reversal. Last, decoupling the hand and eyes when using smooth pursuit produced the longest MT and RespT compared other conditions and not observed with saccades. These data indicated a general slowing for group SmP compared to group SAC. The movement slowing associated with smooth pursuit eye movements also associated with greater endpoint accuracy.

Discussion

In the present study we investigated whether using fixations, smooth pursuit, or saccades affect visually guided reaching during various eye-hand coupling and decoupling tasks in healthy young adults. Our results show that the type of eye movements used influenced temporal movement characteristics of the hand, which were also dependent on the type of eye-hand coupling or decoupling and hand reversal use. In contrast, spatial movement characteristics varied primarily by the type of eye-hand coupling or decoupling and hand reversal use or the type of eye movement used with few interactions. As predicted, using saccades or central fixation led to faster hand movements than smooth pursuit. Furthermore, using smooth pursuit and eye-hand coupling led to more accurate endpoints for hand movements toward targets than saccades and eye-hand decoupling tasks, respectively. We use the following text to discuss spatial and temporal measures independently prior to the spatiotemporal interaction.

Spatial Measures

Instructing participants to control eye movement impacted spatial aspects of the eye-hand coordination tasks primarily through main effects of Group and Condition. Not surprisingly, people in both groups produced the smallest absolute errors when coupling the movements of the hand and eyes toward targets (see EH data in Figures 3.1b and 1c, and Figures 3.2c). Greater absolute errors for decoupled conditions with hand reversal, regardless of the varied path lengths, support results of previous studies as well (Dalecki et al., 2016; Dalecki, Gorbet, & Sergio, 2019). Interestingly, coupling the hand and eyes did not always lead to the best spatial movement planning (compare initial direction error in EH to EF, see Figures 3.2a) but improved spatial endpoint accuracy associated with less separation between the hand and eyes (Salek et al., 2011). Requiring participants to follow their finger toward the target using smooth pursuit likely enhanced unity of the hand and eyes compared to the use of saccades to limit endpoint errors.

Our study results also revealed that people performing smooth pursuit eye movements produced smaller absolute errors compared to people performing saccadic eye movements across all conditions (see Figures 3.2c). Without a smooth pursuit advantage for every condition, we considered the possibility of heteronomous groups; however, links between speed and accuracy discussed under Spatiotemporal Control are reasonable and cannot be ignored.

Temporal Measures

Instructing participants' control over eye movements altered temporal characteristics of hand performance, which depended on Condition. Making the two fixation conditions similar

between groups allowed for more direct comparisons between groups. For each group, hand movements toward targets with eye fixation took less time and greater peak velocities than hand reversal movements with eye fixation (compare EF and EFR for each group, Figures 3.2d and 3.2f). Thus, slower movements and speeds for decoupled eye-hand conditions with eyes moving toward targets compared to coupled movements observed here (compare EH and EHR, Figures 3.2d and 3.2f) and elsewhere (Dalecki et al., 2016; Dalecki, Gorbet, & Sergio, 2019; Salek et al., 2011) was also observed for fixations. The movement slowing during eye-hand decoupling tasks has been explained by an increase in cognitive-motor effort needed to plan and execute the dissociation of the eyes and hand movement directions (Gorbet & Sergio, 2009, 2016). Although no movement execution for the eyes is needed for fixations, dissociation of the eyes and hand still exists without (EF) or with (EFR) the use of hand reversal. These data provide evidence that hand reversal and not eye-hand decoupling caused the slowing during EFR. During movement execution in hand reversal tasks with fixation, the cursor must be moved toward the target without direct guidance of the hand or eyes. The movement slowing during reversal tasks may also be linked to the increased cognitive effort needed to simultaneously keep track of the cursor and finger (Feria, 2013).

Use of saccadic eye movements during coupled movements toward targets produced the shortest reaction times (see Figure 3.2b condition EH), thus the most efficient movement preparation. These results suggest that the 100 ms latency advantage of smooth pursuit (Erkelens, 2006) over saccades (Fuchs, 1967) does not affect the preparation of quick self-initiated movements of the hand to refute the corresponding hypothesis for a smooth pursuit reaction time advantage over saccades. In contrast to saccades, using smooth pursuit eye

movements did not produce a reaction time advantage for coupled over decoupled movements. The saccade coupling advantage over smooth pursuit and fixations may relate to improved visuomotor connections for saccades, as muscle activation for reaching prior to saccadic muscle activation does exist (Gribble et al., 2002). This quick muscle activity of the hand may explain why many people naturally want to saccade to newly presented targets (Song & McPeek, 2009). In the case of smooth pursuit, people must suppress this saccadic instinct and execute a different movement, possibly further extending time to react.

The greatest number of temporal differences between the smooth pursuit and saccade groups was observed for movement time. For response execution, we expected the shortest hand movement, total response times, and greatest peak speeds for participants using saccades because of the faster maximum speed capabilities associated with saccades (Bahill et al., 1975) compared to smooth pursuit (Fuchs, 1967), an advantage that could be used to direct hand movements more quickly. Although no significant group differences existed for fixations when moving toward targets, as expected, an unanticipated movement time group difference for fixations with hand reversal existed, which might be partially explained by a greater number of males in group SAC. Males can reveal shorter movement times and faster speeds than females (e.g. (Loring-Meier & Halpern, 1999)). With randomization of conditions across participants, smooth pursuit and saccade trial experience prior to performing the fixation trials may have also naturally decelerated (group SmP) or accelerated (group SAC) performances in fixation with hand reversal. The slower movement time associated with smooth pursuit eye movements in three of the five conditions may have naturally slowed movements in fixation conditions due

to prior exposure not experienced by group SAC. Review of the data indicated that the … to support this possibility.

Unlike group SAC, participants in group SmP produced the shortest movement/response times and greatest peak speeds for fixation trials in which hand movement was toward the target. Interestingly, coupled movements toward targets using smooth pursuit revealed similar times and peak speeds to decoupled fixations with hand reversal (compare grey plots of EH with EFR, Figures 3.2d and 3.2f). One might argue that the time to produce hand/cursor following smooth pursuit eye movements requires a certain amount of cognitive processing time that compares to the processing and execution time needed for reversal movements. If true, cognitive processing time, and in turn movement time, should increase when using smooth pursuit during reversal tasks, showing the common time dependent dual-processing effect (e.g, (Huxhold, Li, Schmiedek, & Lindenberger, 2006). Indeed, our results indicate that group SmP revealed the longest time to move for decoupled movements with hand reversal and the longest response times and lower peak speeds for coupled and decoupled movements with hand reversal to support such a dual-processing effect. In contrast, similar times and speeds for the reversal tasks were observed in group SAC (see EFR, EHR, ERHR, Figures 3.2d and 3.2f) to support evidence indicating no additional visual processing, thus time to process perceptual visual information occurs during saccadic eye movements (Bridgeman, 1975). With no movement time differences between coupled movements with or without hand reversal for group SAC (compare black EH and ERHR, Figure 3.2d) and shorter movement times for coupled than decoupled movements with hand reversal for group SmP (compare grey EHR and ERHR,

Figure 3.2d), the current results corroborate eye-hand coupling movement time advantages over decoupling (Dalecki, Gorbet, & Sergio, 2019; Gorbet & Sergio, 2019; Salek et al., 2011)

Spatiotemporal Control

The results of this study revealed clear evidence that participants in group SAC spent less time moving the hand at faster peak speeds than those in group SmP in all conditions which did not involve fixations (compare grey and black EH, EHR, ERHR, Figures 3.2d and 3.2f). Furthermore, group SAC also reacted faster than group SmP in conditions involving hand-eye coupling (see grey EH and ERHR, Figure 3.2b). Combined with the smaller endpoint errors for group SmP compared to group SAC in all conditions (Figure 3.2c), these data provide support that our participants were likely influenced by a speed accuracy trade-off (Fitts, 1954). Also, it has been suggested that decoupling eye-hand coordination tasks have a minimum of two processes of motor adaptation, which allows the task to be performed fast with greater errors or slow with fewer errors (Smith, Ghazizadeh, & Shadmehr, 2006). This means that one process focuses on temporal performance while the other focuses on spatial performance. Eye movement selection may incorporate one process instead of the other. This, in combination with the speed-accuracy trade-off, may adequately describe the differences between eye movement selection and task performance.

Other sources that support the spatiotemporal differences observed between groups likely involved idiosyncratic choices among participants and task requirements. Group differences observed for EF and EFR support the potential of idiosyncratic choices. Using two task requirements, which involved different underlying mechanisms, known to affect movement speed cannot be ignored. For example, having people perform smooth pursuit eye

movements, a closed loop task, which requires greater cognitive processing time during movement than saccades, an open loop task (Schenk, Walther, & Mai, 2000), may encourage an overall emphasis on accuracy over speed, often known to slow the movement (Fitts, 1954). Future studies could be used to determine if neurological populations, who produce slower and/or less accurate reversal movements than age-matched healthy controls (Hawkins et al., 2015; Hawkins & Sergio, 2014; Salek et al., 2011; Tippett et al., 2007; Tippett, Sergio, & Black, 2012)could use smooth pursuit movements to improve accuracy or saccades to improve speed. Whether these populations could also become more accurate or faster through rehabilitation strategies which utilize certain eye movements also warrants further investigation.

Study limitations

This study is not without limitations. Using separate groups for tasks involving smooth pursuit and saccades did not allow for within subject analyses for all condition comparisons, which may have led to idiosyncratic performance differences. Instead, we used two fixation conditions with the same instructions for each group that helped us limit the number of trials and the potential experience-dependent improvements. With almost similar performances between groups for the EF fixation conditions, we believe that idiosyncratic differences were not the driving factor behind our results. However, we acknowledge the difference between EFR movement time in each group is a limitation. We also acknowledge that the different proportion of males and females within each group possibly influenced performance outcomes to a certain degree.

Conclusion

Having participants alter the movement of their eyes altered hand movement performance differently during variations of eye-hand coupling and decoupling tasks with and without hand reversal. Performing smooth pursuit, saccades, or central fixation altered temporal and spatial aspects of hand movement. Coupling the eye and hand when reaching toward a target resulted in improved endpoint accuracy compared to decoupling tasks, regardless of eye movement selection (saccades or smooth pursuit). Use of saccades and fixations improved temporal aspects of hand movement compared to smooth pursuit, while use of smooth pursuit revealed improved endpoint errors compared to saccades and in some cases fixation. We expanded the knowledge that eye movement choice, which can influence eye-hand decoupling movements such as operating a driving simulator (based on saccades or fixation performance)(Mackenzie & Harris, 2017), can influence various coupled and decoupled visually guided reaching tasks as well. Our findings expand this information by describing the influence of smooth pursuit eye movements on eye-hand coordination performance. Based on our findings, we suggest researchers should consider providing specific eye movement instructions and/or monitoring with eye tracking technology during performance assessments of discrete goal-directed movements, to account for the potential confounding effects of eye-movement behavior on spatial and temporal aspects of hand movements.

CHAPTER 4. INCREASING COGNITIVE-MOTOR LOAD DECREASES VISUALLY GUIDED REACHING ACCURACY, SPEED, AND STANDING SWAY: STUDY 2

Introduction

In everyday life when we reach for an object, people usually move the eyes and hand toward the same spatial location, coupling the gaze and reach directions. When decoupling gaze and reach directions, people can move the eyes and hand toward spatially incongruent locations. An example of decoupling could involve looking to the left but moving the hand to the right, such as a no-look pass in football. Coupled (i.e., eyes and hand moving towards a target together) and decoupled (i.e., eyes moving toward, while the hand moves away from a target) visuomotor tasks require the incorporation of context-specific rules to guide effectors of the hand and eyes. These visuomotor tasks also involve different levels of cognitive integration (Gorbet & Sergio, 2016) affecting hand kinematics of various populations (Brown et al., 2015; Dalecki et al., 2016; Dalecki, Gorbet, & Sergio, 2019; Hawkins et al., 2015; Salek et al., 2011). Notably, participants performed the eye-hand coordination tasks in a sitting position; however, recent applications involve participants standing during quick sideline concussion screening in contact-sports (Sergio et al., 2017). Understanding whether visuomotor tasks involving cognitive-motor integration differ for sitting and standing participants could provide crucial information applicable to various situations like the sideline screening protocols.

Changes in body position can influence performances in eye-hand coordination. Previous research revealed that pointing errors observed during more constrained sitting positions disappeared, thus improved, when similar tasks were performed while standing upright and less constrained (Hondzinski & Kwon, 2009). In contrast, changing posture from

sitting to standing may degrade eye-hand coordination, since resources used for task performances are also needed for controlling balance when standing compared to sitting (Lajoie, Teasdale, Bard, & Fleury, 1993). Thus, the increased attentional demands during cognitive tasks may diminish postural control (Reilly, van Donkelaar, Saavedra, & Woollacott, 2008). Whether standing posture will improve, degrade, or not influence eye-hand coordination during decoupled visuomotor tasks compared to sitting remains undetermined. One aim of the present study involves addressing the effects of standing posture on performance of visuomotor tasks with different levels of cognitive integration in young adults.

Performing cognitively demanding visuomotor tasks can alter postural control in healthy people (Dierijck et al., 2019; Izquierdo-Herrera, Garcia-Masso, Gonzalez, Wade, & Stoffregen, 2018; Yeomans et al., 2018). Use of visually guided saccadic eye-movements reduced sway compared to external gaze fixation, thus positively enhanced postural control in children (Izquierdo-Herrera et al.) and young adults (Ajrezo et al., 2013; Rodrigues et al., 2013; Rodrigues et al., 2015; Rougier & Garin, 2007; Stoffregen et al., 2007; Yeomans et al., 2018) alike. The addition of subtle hand movements can also reduce sway. Younger and older adults experienced a decrease in postural sway while standing and performing a simple reaction time test compared to standing while eyes were fixated on a stationary target (Huxhold et al., 2006). Some visually guided eye-movements (Stoffregen et al., 2007; Yeomans et al., 2018) and cognitively demanding tasks involving the upper extremity (Huxhold et al., 2006) may act as supra-postural tasks which encourage sway reductions. Attenuation of sway ensures more successful performances of the supra-postural task (Izquierdo-Herrera et al., 2018; Stoffregen et al., 2007). Other, more complex cognitively demanding upper extremity tasks, involving a

reaction time button push, followed by a reaching task can destabilize postural control and increase sway (Dierijck et al., 2019). Whether this postural destabilization resulted from greater upper limb movement, altered eye-movements, greater cognitive effort, or some combination remains uncertain. Thus, the second aim of the present study involves addressing the effects of visuomotor task performances with different levels of cognitive integration on standing posture in young adults.

Results from previous research reveal that people perform eye-hand coupling tasks faster and/or with greater accuracy compared to eye-hand decoupling tasks (Dalecki et al., 2016; Dalecki, Gorbet, & Sergio, 2019; Salek et al., 2011). However, it is not known whether changes in body posture would influence both tasks equally and/or whether the eye-hand coordination tasks would alter sway during stance equally. We addressed two aims in the present study. Specifically, we investigated whether performance of eye-hand coupling/decoupling tasks differed when young healthy participants perform the eye-hand coupling/decoupling tasks sitting or standing and whether performance of eye-hand coupling/decoupling tasks altered postural control differently while standing. We expected an increase in performance duration of decoupled tasks while standing compared to sitting due to increased attentional demands to maintain posture. We also expected that performing eye-hand decoupled tasks, which require greater cognitive demands, would reduce postural displacements compared to performing in the eye-hand coupled tasks.

Methods

Participants

Eighteen college-aged, right-handed healthy young adults *(M =* 21.3 years and *STD* = 0.6, 14 females) with no self-reported history of concussion, diabetes, neuromuscular disease, cardiovascular diseases, or orthopedic diseases participated in this experiment. Participants recruited from Louisiana State University (LSU) signed provided written informed consent prior to participation.

Procedures

A vertical touchscreen on a 15.6-inch laptop computer was used for data collection of hand movements. A central circular target, in the middle of 345 mm x 195 mm screen provided location of the start position. Peripheral circular targets, located up, down, left, and right at a center-to-center distance of 75 mm from the center target, appeared on the screen and provided an end goal. All targets were 20 mm in diameter. The top of the laptop screen was positioned at eye height. Participants sat in a chair or stood at a set reaching distance (80% of arm length) in front of the laptop wearing a black, cloth glove on their right hand. The head and upper body were not restricted. At the beginning of each task trial for condition eye-hand (EH), where eye-hand movement direction was coupled, individuals positioned their finger and a corresponding cross-hair cursor on the center of the central target. Participants were instructed to slide their right index finger, thus cursor, across the screen towards a suddenly appearing peripheral target as quickly and as accurately possible. For the eye-hand reversed task condition (EHR), eye-hand movements were decoupled. Participants were instructed to move the cursor into the center of the given peripheral target as quickly and as accurately possible

using an oppositely directed finger movement. Thus, 180° feedback reversal existed between hand and cursor movement so that moving the finger to the left moved the cursor to the right. Participants were instructed to stand and sit comfortably, while maintaining good posture for each body position. No specific eye-movement instructions were given.

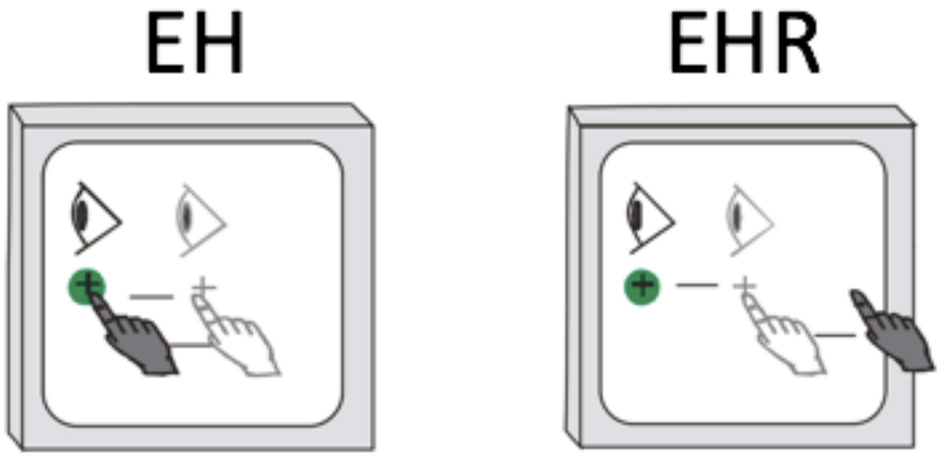


Figure 4.1. Visual representation of the conditions EH (coupled) and EHR (decoupled). EH: eyes and hand move together toward the peripheral target, EHR: eyes move toward the peripheral target when the hand moves away from target. Grey outlines represent eyes and hand at start position, while black outlines and a dark grey hand represent eyes and hand position at movement end.

Data Collection

Height, eye height (e.g., for sitting and standing conditions), and weight were recorded for each participant. A brief description of a condition was provided before participants practiced the given eye-hand coordination task 4 times in each direction; left/right/up/down. After practice, participants performed two rounds of 20 trials for a total of 40 trials with 10 trials in each direction. Target presentation was randomized for each condition. Conditions were randomized within a body position which was pseudorandomized across participants, so that half the participants completed standing trials before sitting trials and the other half

completed sitting trials before standing trials. When the software detected that participants did not stop inside the target, the trial was repeated later within the same round and the inappropriate trial was removed offline. This left 160 trials for each subject available for further analyses.

Hand movements were collected using a special computer code used to present the targets and cursor movement and record the cursor data at 60 Hz (BrDI™). A mobile eye tracker was used to record eye-movements and monitor hand movement video at 60 Hz to ensure instructions were followed (SMI, Teltow, Germany). Calibration of gaze position was achieved by performing a three point fixation calibration using manufacture guidelines. Gaze position was monitored during data collection and recalibrated when drifting occurred between rounds. Force data needed to calculate center of pressure (CoP), thus sway variables, were collected at 100 Hz using an AMTI force plate (AMTI, Watertown, MA, USA) for each round. Participants performed standing trials with a narrow base of support. Participants heels were placed 3 cm apart while feet remained parallel to one another during standing trials. Each participant performed standing trials barefoot, and foot outlines ensured that foot position was consistent throughout the trials for each person.

Data Analysis

Frame-by-frame review of point of gaze and hand movement video data recorded with the eye tracker using BeGaze software (SMI, Teltow, Germany) helped determined whether eye-movements performance in each trial could explain differences between participants with abnormal results. For the hand movements, the x and y coordinates of the cursor position were recorded during each trial. Remember that the cursor position was controlled by the finger

movement. Raw position data were converted into MATLAB readable format using a custom written C++ application. Individual movement paths derived from the cursor location were low-pass Butterworth filtered at 10Hz (Matlab, Mathworks Inc.) prior to use of a customized MATLAB program used to calculate spatial and temporal variables. The software detected the initiation and end of a movement at 10% of peak velocity similar to elsewhere (Dalecki, Gorbet, & Sergio, 2019). Movement start and end of each trial were inspected by an experienced analyzer. If the program labeled them incorrectly or was not able to detect the start or end automatically, the analyzer provided a frame where it could define the correct start and or end in accordance with the 10% threshold.

Variables of interest for hand movements included temporal variables (reaction time—RT, movement time—MT, response time—RespT, and peak velocity—PV) and spatial variables (absolute initial direction error—aIDE, path length—PL, and absolute endpoint error—AE). For the temporal measures, RT (milliseconds; ms) was defined as the time interval between target presentation and cursor movement onset. MT (ms) was defined as the time interval between movement onset and end. RespT (ms) was movement time plus reaction time. PV (mm/s) was defined as the cursor's peak velocity during movement. For the spatial variables, aIDE (°) was defined as the angle between cursor position at movement onset and at 100 ms after movement onset in relation to the straight line between the centers of the central and peripheral target circles. PL (mm) was defined as the trajectory path between movement onset and end. AE (mm) was defined as absolute distance between cursor endpoint and target center.

Sway data (Center of pressure--CoP) were analyzed from raw data obtained from balance clinic software (version 2.03.00) associated with the AMTI force plate. CoP

displacement variables were normalized according to task completion time of each condition, because trial length varied. CoP variables of interest included normalized medio-lateral displacement—nML—the average x displacement of CoP divided by the time of the trial, normalized anterior-posterior—nAP—the average y displacement of CoP divided by the time of the trial, normalized radial displacement—nRD—the average radial position vector length divided by the time of the trial, and velocity—VEL—the average CoP path length per second. . Mean variables represent the average of each condition (EH, EHR) and body position (sitting, standing) for each participant. Note that variables associated with hand movement represented trial means, while variables associated with CoP represented means across rounds.

Statistical Analysis

Data were checked for normal distribution using a Shapiro-Wilk's test. For normally distributed data, a two-way repeated measures ANOVA was used to determine if hand movement variables differed by Condition (EH, EHR) or Body Position (sitting, standing). A repeated measures ANOVA was used to determine if CoP variables differed by Condition (EH, EHR) within the Body Position (sitting, standing). Bonferroni corrections were used for post-hoc analysis. For non-normally distributed data, data were either log transformed then analyzed as previously described or analyzed using non-parametric statistics when transformations did not result in normal distributions. Non-parametric analyses involved use of Friedman ANOVAs and Wilcoxon matched-pair tests with Bonferroni corrections. Statistical significance was set at the standard p-value of 0.05 using SPSS version 25 (IBM, Inc., NY, USA).

Results

Eighteen participants were self-identified as right handed; however, one was considered to be ambidextrous according to the Edinburgh exam, as assessed by the Edinburgh handedness exam (<40, (Salek et al., 2011)). Each person reported no difficulty viewing the screen targets and cursor within arm's length with visual acuities of 20/40 or better (acuity needed to read road signs and make adequate driving decisions, (Owsley & McGwin, 2010)).

For hand movements, MT ($F_{(1,17)}$ = 127.84, *ES* = 0.88, $P < 0.05$, Figure 4.2a), RT ($F_{(1,17)}$ = 173.99, *ES* = 0.91, $P < 0.05$, Figure 4.2b), PV ($F_{(1,17)}$ = 51.82, *ES* = 0.75, $P < 0.05$, Figure 4.2c), and AE ($F_{(1,17)}$ = 42.02, *ES* = 0.71, $P < 0.05$, Figure 4.2d) differed by Condition (see Figure 2). MT and RT for EHR exceeded EH. Accordingly, PV for EH exceeded EHR, while AE for EHR exceeded EH. No other significant differences existed for hand variables.

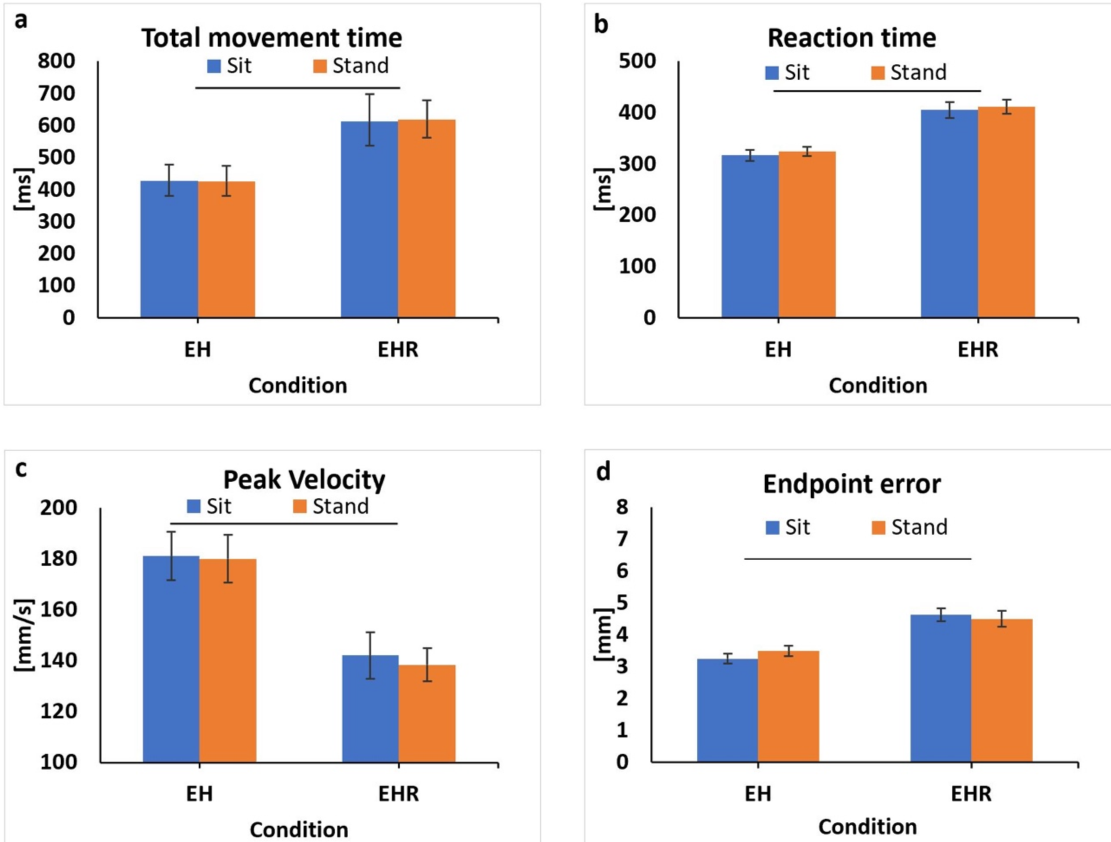


Figure 4.2. Mean values of hand data. Mean values are shown for **a)** total movement time (MT), **b)** reaction time (RT), **c)** peak velocity (PV), and **d)** endpoint error (AE) across subjects for each condition while sitting (blue) and standing (orange). Error bars represent 95% confidence intervals for MT and +/- 1 SE for RT, PV, and AE. Horizontal black lines reveal differences between means for decoupled (EHR) and coupled (EH) conditions.

For postural sway, significant Condition effects for nAP ($F_{(1,34)}$ = 5.984, *ES* = 0.146, P < 0.05, Figure 4.3a), nML ($F_{(1,34)}$ = 23.693, *ES* = 0.404, P < 0.05, Figure 4.3b), and nRD (χ^2 = 7.111, P < 0.05, data not shown due to similarities to nAP/nML) revealed lower values, thus less displacement, for EHR compared to EH during standing conditions. Condition effects on VEL were not significant (P > .05).

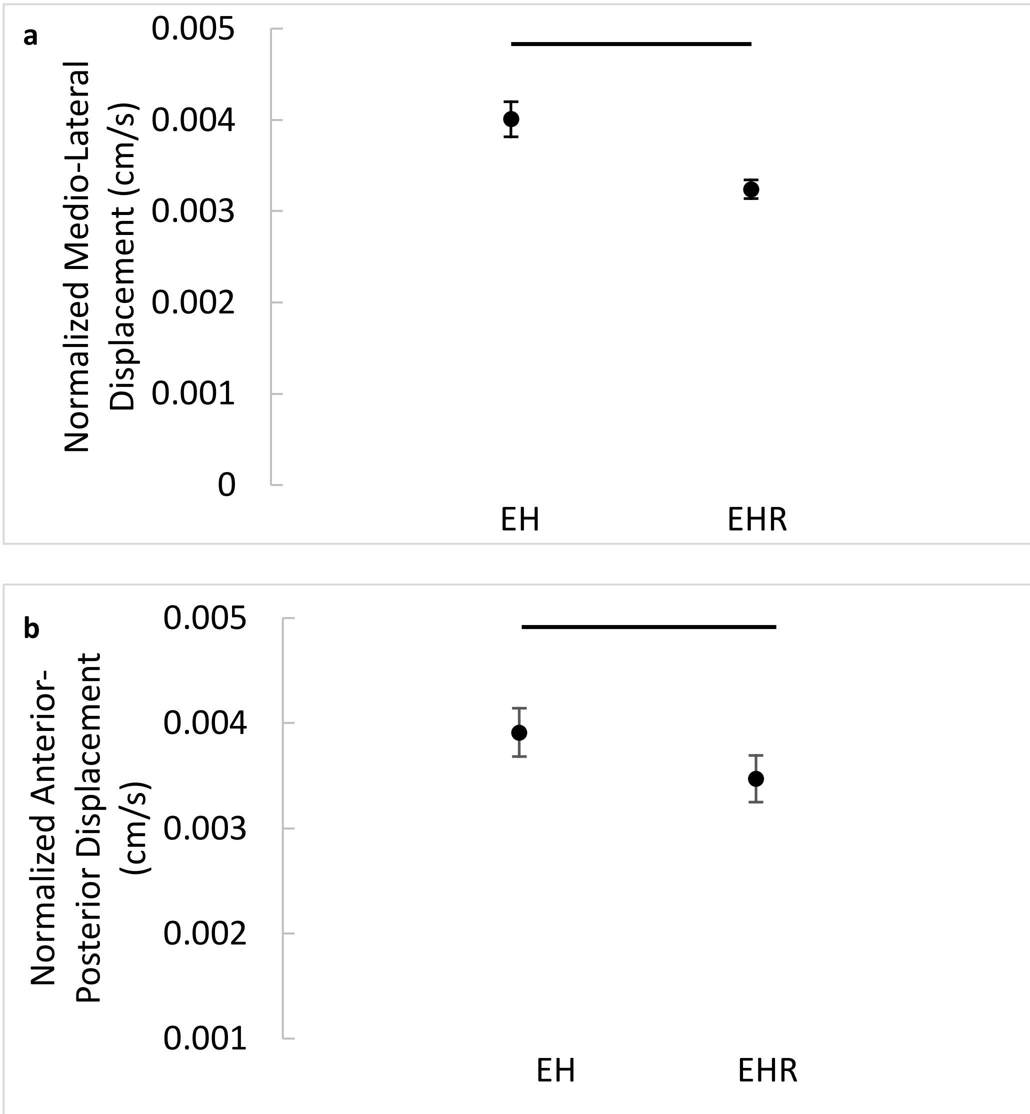


Figure 4.3. Plots of CoP data. Mean values are shown for **a)** normalized medial-lateral (nML), **b)** normalized anterior-posterior displacement (nAP) across subjects for each condition while standing. Error bars represent +/- 1 SE. Horizontal black lines reveal differences between means of decoupled (EHR) and coupled (EH) conditions.

Discussion

In the present study we investigated whether visually guided reaching performance with different levels of cognitive integration (coupled or decoupled eye-hand movements) differed when performed by participants sitting or standing. We also assessed whether standing postural control differed when participants performed coupled or decoupled eye-hand

coordination tasks. Contrary to our prediction, results indicated that eye-hand coordination task performance when the eyes and hand moved together (coupled task) or when they moved to different spatial locations (decoupled task) were not affected differently for standing or sitting body positions. In contrast and as predicted, postural control during standing differed during performance of coupled and decoupled eye-hand coordination tasks so that participants swayed less when the eyes and hand moved to distinct spatial locations compared to when eyes and hand moved to the same spatial location. Therefore, standing did not degrade eye-hand coordination performance, and the more cognitively demanding visuomotor task reduced sway during static stance conditions. In the following text, we discuss performance control differences in the visuomotor tasks with different levels of cognitive integration, and how these differences may interact with postural control.

Hand Performance

The longer performance duration and greater endpoint errors in the decoupled compared to the coupled condition supports results from multiple studies, revealing poorer performance for tasks involving increased cognitive-motor integration (Brown et al., 2015; Dalecki et al., 2016; Dalecki, Gorbet, & Sergio, 2019; Gorbet & Sergio, 2016; Hawkins & Sergio, 2014; Salek et al., 2011). However, similar eye-hand coordination existed for sitting and standing positions, regardless of coupling type. Thus, our results did not support initial expectations that standing up would influence the efficiency of the decoupled task associated with eye-hand movement decoupling due to the fewer available resources for dual processing of upper limb and postural control (e.g., (Huxhold et al., 2006)). Thus, the greater attentional resources used for standing compared to sitting (Lajoie et al., 1993) did not sufficiently alter the

reaches performed in this study. One potential explanation involves the possibility that although standing increased attentional resources over sitting (Lajoie et al., 1993), it also eased reaching performances over sitting, allowing freer body rotations (Hondzinski & Kwon, 2009). Having participants produce relatively small movements limited this possibility. Furthermore, review of the sitting endpoint errors for a few participants verified similarities between rightward and leftward movements expected with non-restricted, thus free movements. We reasoned that other explanations linked to postural control likely explained similarities between body positions, which will be discussed below.

Sway Measures

Participants swayed less when performing the eye-hand decoupled task, in which eyes and hand moved to distinct locations. Swaying less might result from increased attentional demands (Rey et al.), possibly associated with the greater cognitive demands of the decoupled task (Dalecki, Gorbet, & Sergio, 2019; Gorbet & Sergio, 2009). However, eye-hand decoupling may also serve as a supra-postural task, allowing participants to attenuate sway to prevent greater eye-hand coordination deficits during the decoupled task (Izquierdo-Herrera et al., 2018; Stoffregen et al., 2007; Yeomans et al., 2018). Recently, researchers posed the possibility that control for the reduced sway may combine the use of a supra-postural task and higher attentional demands (Yeomans et al., 2018) so that greater attention needed for decoupling made the task supra-postural. Supporting data include that the use of greater cognitive efforts, such as attention required for response inhibition during a color-word- Stroop task, can increase co-contraction of lower extremity muscles and stabilized sway (Melzer, Benjuya, & Kaplanski, 2001). Notably, the higher cognitive demand of the decoupled task condition from

the present study requires response inhibition as well to suppress the naturally impulse to align eye-hand movements (Gorbet & Sergio, 2009). Together these data provide evidence that the reduced postural sway, observed when performing decoupled tasks, may have resulted from an increased co-contraction of lower extremity muscles to limit sway (Melzer et al., 2001) in order to successfully perform eye-hand coordination tasks.

Alternatively, the decreased sway may have been a result of the decreased hand velocity during the decoupled task, and in turn, the higher velocity during the coupled condition may have destabilized sway (see Figure 4.2c). However, researchers have shown that faster arm peak velocities may rather lead to decrease CoP amplitude in both, healthy individuals and neurologic populations (i.e., Parkinson's patients) (Su et al., 2014). Therefore, we believe that the hand velocities had minute influence, if any, in our study and that postural changes were more likely linked to cognitive-load differences between the both visuomotor task conditions.

Movement Control

Results of the present study revealed similar eye-hand coordination for standing or sitting body positions and alterations in hand movements and postural sway between the coupled and decoupled eye-hand movement tasks. Specifically, the performance of reaches requiring greater cognitive demands influenced hand kinematics and posture differently than performances of reaches requiring less cognitive demands. Without evidence to support the use of postural sway influences on hand kinematics, these data seem to support the use of the same cognitive-motor neural controller for reaching and postural control. Opposing outcomes indicating poor performance of hand movements and improvements in posture sway contradict the use of this common control system. Another consideration for control involves

functionality. One function of the postural system is to stabilize the visual system to help direct gaze accurately (Stoffregen, Hove, Schmit, & Bardy, 2006; Stoffregen et al., 2007). We also know that gaze direction functions to provide a control signal for reaching movements (Hondzinski & Cui, 2006) to support the presence of a common neural network controlling gaze and limb movements (Admiraal, Keijsers, & Gielen, 2004; Engel, Anderson, & Soechting, 2000; Engel & Soechting, 2003; Soechting, Engel, & Flanders, 2001). The gaze requirements were similar between the coupling and decoupling condition (i.e., 'move the eyes towards the target'). Thus, it appears that the additional cognitive-motor integration requirements for the rule-based decoupling of vision and motor action (Gorbet & Sergio, 2016) also increased the supra-postural demands to yield greater sway attenuation (Izquierdo-Herrera et al., 2018; Yeomans et al., 2018)for performances in the EHR condition. In other words, sway was modulated to support controlling of the complex, cognitively demanding, eye-hand coordination task. These data provide initial evidence to suggest the existence of a complex interlinking neural network guided by a common goal-directed controller. However, more research is required to provide further support this notion.

Study limitations and future directions

The major limitation of the present study links to level of postural threat. Postural threat was very low in this study for the participants used, yet increasing postural threat might actually influence eye-hand coordination. Further studies could be used to determine whether eye-hand coordination with varied levels of cognitive-motor integration varies when postural control is manipulated. For example, altering foot positioning (i.e., tandem stance) which alters postural control. Another way to alter postural threat is to use an aging and/or neurologically

impaired populations known for poor balance control. Neurologically impaired populations, such as individuals with mild cognitive-impairment, early dementia, or concussion history showed eye-hand coordination deficits during the decoupled but not during the coupled task condition compared with healthy age-matched controls(Brown et al., 2015; Hawkins & Sergio, 2014; Salek et al., 2011). It will be interesting to see whether the current pattern of findings hold true in these populations as well, or if changes in posture and/or postural control will surface additional performance declines in the decoupled eye-hand coordination in the neurological population only.

Conclusion

Performing visually guided movements with greater levels of cognitive integration influenced hand kinematics and standing posture, while standing did not influence visually guided movements with varied levels of cognitive integration. At first these data seem to support the use of a simple neural controller with only affecting postural control. However, because the degradation in hand kinematics did not match the improvement in postural sway with increased cognitive demands, we reasoned that participants limited sway in the decoupled task to limit further potential declines of upper limb performance. Moreover, we suggest participants in this study used on a common goal-directed controller to limit potential postural influences over eye-hand coordination.

CHAPTER 5. CEREBRAL ACTIVITY DURING EYE-HAND COUPLING/DECOUPLING TASKS IN AEROBICALLY FIT VERSUS SEDENTARY POPULATIONS: STUDY 3

Introduction

A high physical fitness level can associate with positive cognitive abilities and sensorimotor abilities with cognitive integration (i.e., Dupuy et al., 2015). Cognitive abilities such as executive functions, including attention, learning, working memory, and problem solving, of young women with higher aerobic fitness levels exceeded young women with lower fitness levels (Scott et al., 2016). Evidence for better sensorimotor abilities with cognitive integration for motor skills also exists. Individuals between 18-35 years old with a high VO_2 max achieved higher relational memory scores, measured using a spatial reconstruction (SR) task compared to individuals with a low VO_2 max (Schwarb et al., 2017). The SR task required people to use a computer mouse to reposition four line segments to match a remembered spatial orientation of the line segments. Women between 19-34 years old with a high aerobic fitness level determined by a graded ergometer test attained shorter reaction times reporting text representation of a color and actual word color incongruences on a computerized Stroop test than individuals with a low aerobic fitness level (Dupuy et al., 2015). In this case it took less fit people more time to name the ink color (say “green”) of letters typed to spell another color (blue) than more fit people. Elsewhere, young fit adults produced greater post-error accuracy corrections than lower fit young adults while completing a flanker task, in which they used a button press to correctly identify greater than or less than signs as either congruent (>>>>> or <<<<<) or incongruent (>><>> or <<><<) (Themanson et al., 2008). Undoubtedly, young adults

with high fitness levels perform better on cognitive assessments and/or sensorimotor tasks with cognitive integration than their lower fit counterparts (Dustman et al., 1990).

Assessments such as the Stroop and Flanker tests, which provide insight into cognitive declines in people, may not be sensitive enough to reveal more subtle neurological changes associated with sensorimotor control. Assessments, known to provide good sensitivity and representation of neurological changes associated cortical declines due to injury (Dalecki et al., 2016) and disease (Tippett et al., 2007) involve sensorimotor tasks with cognitive integration that challenge spatial accuracy and temporal quickness, such as separately directed or decoupled eye and hand movements. Determining whether performance on eye-hand decoupling tasks can also reflect neurological changes associated with fitness level remains unknown, thus is the primary aim of the present study.

Better performance outcomes associated with fitness level, cognitive-sensorimotor interactions, and age accompany brain activity differences. The default mode network (DMN), which involves a highly integrated brain network, including the hippocampus, inferior parietal lobe, medial prefrontal cortex, and posterior cingulate cortex (PCC) (Herting & Nagel, 2013), is one area interest because negative DMN alterations occur with aging and age-related diseases (Boraxbekk et al., 2016). Improved functional connectivity, involving increased PCC perfusion, is positively associated with higher levels of physical activity markers, including lower BMI, smaller waist circumference, and normal blood pressure, in adults of diverse age (Boraxbekk et al., 2016). Greater DMN deactivation, associated with improved executive functions, existed in highly aerobically fit young adult males compared to their sedentary counterparts (Raichlen et al., 2016). In addition, researchers reported greater electroencephalography (EEG) beta phase

synchronization in fronto-parietal sites (Fz, Cz, Pz), and improved cognitive performance in higher fit young adults compared to lower fit young adults performing the incongruent portion of a Stroop task (Wang et al., 2019). This greater beta synchronization, defined as increased beta amplitude, observed in incongruent tasks by higher fit individuals may denote better top-down control of attention related to better cognition/executive functioning (Wang et al., 2019). Different fitness levels can also link to altered activity of event-related potentials (ERP). Highly fit individuals revealed fewer errors and a greater ERP, while performing a flanker task, compared to lower fit individuals (Themanson et al., 2008). Visual stimulation, involving lights flashing at different intensities, produced shorter ERP latencies in high fit younger/older adults compared to low fit older adults (Dustman et al., 1990). In these cases, higher fitness levels/exercise participation appears to serve as an effective tool to increase activity (Gutmann et al., 2015; Hubner et al., 2018) or refine neural circuitry due to fewer, and more specific formation of connections (Krafft et al., 2014). Specifically, aerobic exercise and fitness levels are strongly linked to cortical activity that improve cognitive and motor functions, such as better attention and memory (Field et al., 2010; Gutmann et al., 2015; Vonk et al., 2019) and more efficient motor processing (Hubner et al., 2018). Whether the connectivity changes associate with increased fitness levels or simply participating in physical activity remains unclear (Voss et al., 2016). Regardless, a second aim of the present study involved monitoring brain activity of people with different fitness and activity levels while they performed eye-hand coordination tasks with different cognitive demands, to assess potential differences in cortical control.

When asking people to decouple movements of the eyes and hand during visually guided goal-directed tasks, they achieved slower and less accurate hand movements compared

to coupling movements of the eyes and hand (Brown et al., 2015; Dalecki et al., 2016; Dalecki, Gorbet, & Sergio, 2019; Hawkins & Sergio, 2014; Salek et al., 2011). Reductions in body sway, thus altered postural control, also accompanied performances of decoupled compared to coupled eye-hand coordination tasks (Yeomans, Yan, Hondzinski, & Dalecki, 2020). With physical fitness deemed a confounding factor of body sway (Reynard, Christe, & Terrier, 2019) and sway increases observed in less fit individuals (e.g., (Blaszczyk, Cieslinska-Swider, Plewa, Zahorska-Markiewicz, & Markiewicz, 2009)), one might argue that the sway reductions associated with decoupled performances in sedentary individuals would exceed those for highly fit people. We assessed the potential fitness level effects on eye-hand decoupling directly in the present study.

Assessments which involve eye-hand decoupling, thus greater challenge to spatial accuracy and temporal quickness of hand movements, provide good sensitivity and representation of neurological changes associated cortical declines due to injury (Dalecki et al., 2016) and disease (Tippett et al., 2007). It is unclear whether these assessments are sensitive enough to characterize the more subtle alterations in cortical activity associated with reductions in aerobic fitness and/or physical activity levels. It is also unclear how the increases in postural sway, also associated with reductions in aerobic fitness and/or physical activity levels, might contribute to performance on these assessments. Therefore, we investigated whether fitness level (sedentary; highly fit) of young adults affected eye-hand coordination and/or balance during the performance visuomotor tasks involving various levels of cognitive demands. Observing cerebral activations during performances allowed us to verify whether cortical activity related to fitness level of our participants and/or cognitive load associated with

performances of different eye-hand coordination tasks, as well as postural changes. We hypothesized the existence of different cortical activations (direction dependent on the variable of interest) for eye-hand decoupled task performance compared to eye-hand coupled task performance and for highly fit compared to sedentary individuals. We also hypothesized that highly fit people would produce faster hand movements during decoupled performances compared to sedentary individuals. Our last hypotheses involved the expectations of body sway reductions during decoupled task performance compared to coupled task performance and for highly fit compared to sedentary people.

Methods

Participants

Seven college-aged (*M* = 21.3 years and *STD* = 2.4, 3 females) adults participated in this experiment. Participants were recruited from Louisiana State University. All participants were right handed, as assessed by the Edinburgh handedness exam (>40 was considered to be right-handed (Salek et al., 2011)), with visual acuity 20/40 or better (acuity needed to read road signs and make adequate driving decisions (Owsley & McGwin, 2010)) and had no self-reported history of concussion, diabetes, neuromuscular disease, cardiovascular diseases, or orthopedic diseases.

Participants provided additional information regarding fitness levels and physical activity levels using International Physical Activity Questionnaire (IPAQ 2002) to determine qualification and group allocation according to the following. Participants for the highly fit group included young adult distance athletes from the surrounding community, while participants for the sedentary group included young adults with no current or recent past exercise/training. Fitness

level determination was set according to American College of Sports Medicine (ACSM) guidelines (Pescatello, 2014). Highly fit participants, achieved a VO_{2max} of at least 50 ml/kg/min. Sedentary participants, who participated in less than 30 minutes of physical activity 3 times a week for 6 months or more with no history of high fitness levels, achieved a VO_{2max} of no more than 34 ml/kg/min.

Procedures

Data collections were performed on two separate days. VO_{2max} was estimated using a submaximal fitness test on the first day, in order to properly identify group classification as highly fit or sedentary or not qualified for the study. The YMCA sub maximal cycle protocol test was performed using a cycle ergometer. Participants cycled at 50 rev/min at an initial workload of 25 watts. The workload increased based on heart rate values after each 4-minute stage, until they reached 85% of their calculated maximal heart rate (i.e., 220-Age). VO_{2max} was measured as the maximal oxygen consumption achieved during exercise testing using a Parvomedics True Max 2400 Metabolic Measurement Cart (Salt Lake City, UT). This exercise test provided physical measures of fitness level needed to define groups as described previously. Ratings of perceived exertion (RPE) were also obtained using the Borg scale during each minute of exercise testing, to ensure exertion levels did not maintain a perceived maximum for more than two minutes during the exercise test. If a participant qualified for the study they returned within three weeks for a second data collection.

Upon arrival to the lab for the second collection day, information regarding race, age, health, anthropometry (i.e., height, eye height, weight), and time of collection were recorded. Participants provided information about their sport/gaming experience to account for potential

outliers in performances. Prior to task performance, participants were equipped with a mobile eye tracking device (SMI, Teltow, Germany) and 32 channel EEG cap (Brain Products GmbH, Zeppenlinstrasse, Germany). Calibration of gaze position was achieved by performing a three point fixation calibration using manufacture guidelines. Gaze position was monitored during data collection and recalibrated when drifting occurred between rounds. After measuring participants head circumference, the correctly sized EEG cap was placed on the head and securely fastened. EEG gel was applied to each electrode/scalp until we saw an adequate signal from each electrode (Figure 5.1). EEG pre measures were recorded under two conditions. Participants were instructed to stand and stare at a point while thinking about nothing for one minute. We used the eyes open pre measure for normalization of data. The pre measure involved participants standing comfortably with no foot placement specifications.

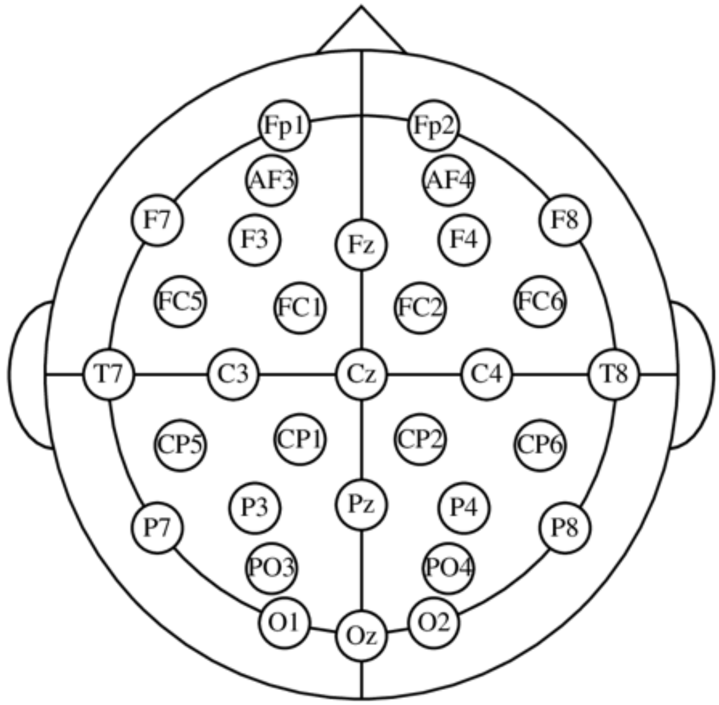


Figure 5.1. Visual representation of EEG electrode placement. The following visual diagram shows the EEG electrodes placement that were used in this study: frontal areas (Fz, F3, F4, F7), central areas (Cz, C3, C4); centro-parietal areas (CP1, CP2, CP5, CP6); and parietal areas (P3, P4, P7). Reprinted from "EEG-Based Emotion Recognition Using a Wrapper-Based Feature Selection Method," by AbdelAal, Alsawy, & Hefny, 2018, *International Conference on Advanced Intelligent Systems and Informatics*.

Once equipped, participants stood with feet in a narrow base of support (see details below), at a distance of 80% of arm length, in front of a vertical touchscreen on a 15.6-inch laptop computer used for data collection of hand movement records. A central target, in the middle of 345 mm x 195 mm screen provided location of start position. Peripheral circular targets (20 mm in diameter), located up, down, left, and right at a center-to-center distance of 75 mm from the center target, provided end movement locations. Targets were presented slightly below eye height (top of touch screen laptop was positioned at eye height) under two different conditions (Figure 5.2). EH involved the eyes and hand moving to the peripheral target. For EH participants slid their finger on the vertical touch screen to move a cursor from

the central target to one of four peripheral targets so that finger position directed, thus matched cursor position. EHR involved the eyes and cursor moving to the peripheral target, while the hand moved in the reverse direction away from the peripheral target. Finger position for EHR directed cursor position through a 180 degree reversal.

After a brief description, a trial proceeded as follows for each condition (Figure 5.2). At the beginning of each a round for EH, individuals started with their right index finger and cross-hair cursor in the center of a central target (start position) that appeared in the middle of the screen. Then they slid their finger across the screen to a suddenly appearing peripheral targets as quickly and as accurately possible. Once in the peripheral target, participants held their finger in place until the center target reappeared, then slid it back to the center target to prepare for the next trial. For EHR, participants started the same as EH and were told to move the cursor to the center of a peripheral target when it suddenly appeared on the screen. They were instructed to slide the finger from center target peripherally in the opposite direction of the peripheral target so that the cursor ended in the center of the given peripheral target, as quickly and as accurately possible. Again, once in the peripheral target, participants held their finger in place until the center target reappeared, then slid it back to the center target.

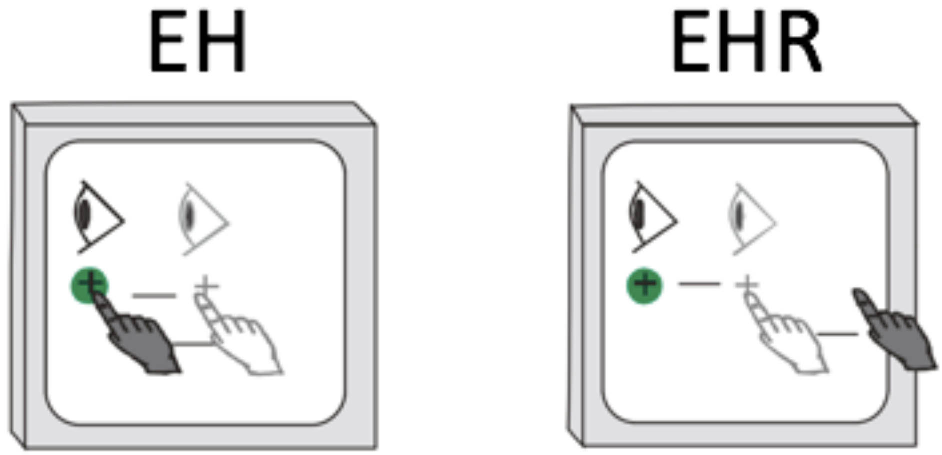


Figure 5.2. Visual representation of the 2 conditions. Grey outlines represent eye and hand at start position, while black outlines and dark grey hand represent eye and hand position at movement end. The figures represent the experimental conditions-EH: eyes and hand to peripheral target, EHR: eyes to peripheral target and hand away from target. The plus sign refers to the cursor start (grey) and end (black) positions, while the green target represents the peripheral, endpoint target.

After completing three rounds of each condition, post EEG measure were recorded using the same procedure as the pre EEG measure. Due to interference between EEG and force plate signals, participants completed only two rounds of eye-hand coordination tasks (1 per condition) in order to obtain postural balance measures.

Each round of the given condition included 16 trials (total of 48 trials for each condition; 12 in each direction for EEG data collection but only 4 in each direction for force plate data collection). Target presentation was randomized for each condition. Both conditions were performed while standing. Participants completed tasks with EEG measures prior to tasks with force plate measures because our primary interests were related to cerebral activation differences.

Hand movements were collected using a customized software application used to present the targets and cursor movement and record the data at 60 Hz (BrDI™). Spatial (absolute initial direction error, path length, and endpoint error) and temporal (total movement time, response time, reaction time, and peak velocity) variables were then calculated using a specific MATLAB program. A SMI mobile binocular eye tracker (SMI, Teltow, Germany) was used to record eye movements at 60 Hz to ensure instructions were followed. Force data needed to calculate center of pressure (CoP), thus sway variables, were collected at 100 Hz using an AMTI force plate (AMTI, Watertown, MA, USA) for each round. Participants performed standing trials with a narrow base of support. Participant's heels were placed 3 cm apart while feet remained parallel to one another during standing trials. Each participant performed standing trials barefoot, and foot outlines ensured that foot position was consistent throughout the trials for each person even when the force plate was off during EEG data collection. EEG data from 32 electrodes were collected using a Brain Products international 10/10 system cap and software at 500 Hz (Brain Products GmbH, Zeppenlinstrasse, Germany, Figure 5.1). Cellphones were turned off during collection to avoid any electrical interference with EEG data. EEG recordings were started about within three seconds of starting a round and stopped around three seconds after round completion. Rounds were manually marked during data collection so that a researcher pressed a button at the beginning of each round, defined as the participant touching the central target for the first time in the round, and at the end of each round, determined as the completion of finger movement to last target within a round. For force plate trials, a researcher pressed a start button at the beginning and end of each round, according to the same guidelines just mentioned.

Data Analysis

Frame-by-frame review of point of gaze and hand movement video data recorded with the eye tracker helped determined whether eye movements performance in each trial could explain differences between participants with abnormal results. Raw position data were converted into MATLAB readable format using a custom written C++ application. Individual movement paths derived from the cursor location were low-pass filtered at 10Hz (Butterworth) prior to use of a customized MATLAB program to calculate spatial and temporal variables (Matlab, Mathworks Inc.). The program detected the initiation and end of a movement at 10% of peak velocity similar to elsewhere (Dalecki, Gorbet, & Sergio, 2019). Movement initiation and end of each trial were inspected by an experienced analyzer. If the program labeled them incorrectly or was not able to detect the start or end automatically, the analyzer provided a frame where it could define the correct start and or end in accordance with the 10% threshold.

Variables of interest for hand movements included temporal variables (reaction time—RT, movement time—MT, response time—RespT, and peak velocity—PV) and spatial variables (absolute initial direction error—aIDE, path length—PL, and absolute endpoint error—AE). For the temporal measures, RT (milliseconds; ms) was defined as the time interval between target presentation and cursor movement onset. MT (ms) was defined as the time interval between movement onset and end. RespT (ms) was movement time plus reaction time. PV (mm/s) was defined as the cursor's peak velocity during movement. For the spatial variables, aIDE (°) was defined as the angle between cursor position at movement onset and at 100 ms after movement onset in relation to the straight line between the centers of the central and peripheral target circles. PL (mm) was defined as the trajectory path between movement onset

and end. AE (mm) was defined as absolute distance between cursor endpoint and target center. Each variable was averaged over each 3 rounds for both conditions during EEG collection.

EEG data were analyzed offline after collection in a specific Brain Products analysis software, then exported for statistical analysis. Similar to elsewhere (Beurskens, Steinberg, Antoniewicz, Wolff, & Granacher, 2016), offline analyses involved filtering data with a low cutoff filter at 0.5 Hz and a high cutoff filter at 70 Hz (2nd order), and was followed by a notch filter at 60 Hz. Blinks were then removed from the data using ocular correction with independent component analysis. Semi-automated data inspection rejected artifacts accordingly (gradient: <35 mV; amplitude range -100 to 100 mV). The data were then inspected by the researcher who removed any confounding or artifact related signal, then separated into individual trials. Trials were analyzed using spectral analysis, Fast Fourier Transformation (FFT) with a Hanning window of 10%, with a resolution of 0.5 Hz and were averaged across each trial. This spectral analysis allows us to decompose the frequency down to constituent frequencies (i.e., alpha and beta), and the Hanning window attempts to prevent spectral leakage. Trial data were then divided for average voltage activity at the following amplitudes: delta (0.5 Hz-3.5 Hz), theta (3.5 Hz-7.5 Hz), alpha (8 Hz-12 Hz), and beta (12 Hz-30 Hz). Trial data for each amplitude were averaged for each condition/participant. The difference between average amplitude and participant's corresponding pre measure allowed us to obtain amplitude activity normalized by resting state. These values were used to determine significant differences between conditions at the following channel sites: frontal areas (Fz, F3, F4, F7), central areas (Cz, C3, C4); centro-parietal areas (CP1, CP2, CP5, CP6); and parietal areas (P3, P4, P7).

Sway data (Center of pressure--CoP) were analyzed from raw data obtained from balance clinic software (version 2.03.00) associated with the AMTI force plate. They were normalized according to task completion time of each condition, because trial length varied. CoP variables of interest were normalized medio-lateral displacement—nML, normalized anterior-posterior—nAP, normalized radial displacement—nRD, path length—PL, and velocity—VEL. A MATLAB program was used to normalize CoP data that were collected from the force plate. nML was determined as the average x displacement of CoP from platform center divided by the time of the trial. nAP averages were determined in the same manner as nML, but in the y direction. nRD was determined to be the average radial position vector length divided by the time of the trial. PL was determined to be the entire path length of the CoP for the duration of the trial. VEL was determined to be the average CoP path length per second.

Mean variables of interest for hand movement and EEG data were determined for each condition and participant for analyses associated with EEG data collections. Mean variables for hand movements and single sway variables were used for analyses associated with force plate data collections.

Statistical Analysis

Remember, data were collected separately due to signal interference, thus were also analyzed separately too. Mixed model ANOVAs were performed on each mean variable using the within subject factor of Condition (EH, EHR) for EEG/force plate trials and between subject factor of Group (Highly Fit, Sedentary). Statistical significance was set at the standard p-value of 0.05. Tukey's HSD tests were used for post-hoc analysis. Analyses were performed using TIBCO Statistica (TIBCO Software Inc. version 13.3).

Results

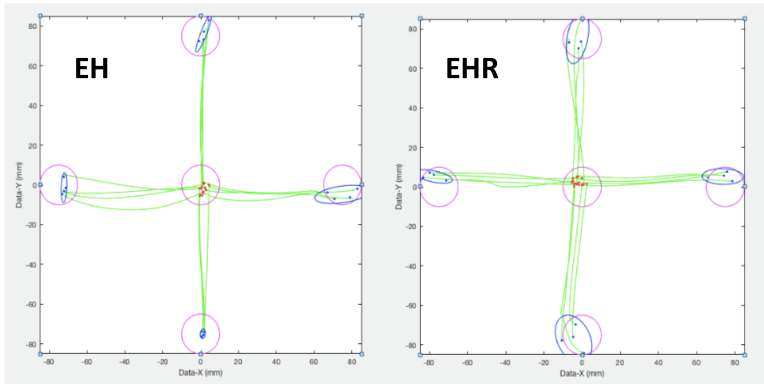
Table 5.1 shows the estimated VO_{2max} for each participant, as well as the group that the participant was assigned to after testing. Note the differences between estimated VO_{2max} measures when comparing participants in different groups.

Table 5.1 Results of submaximal testing

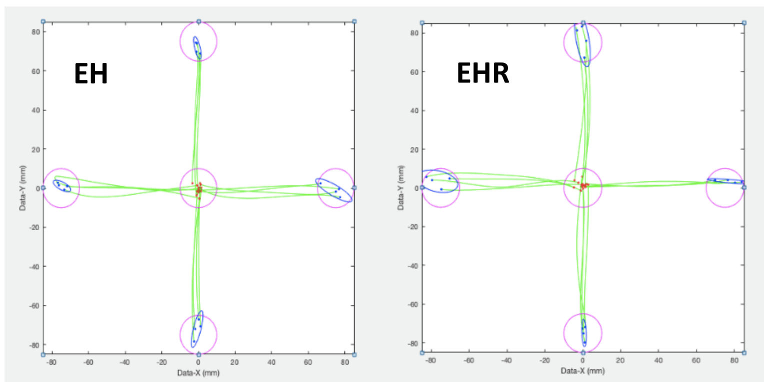
Participant #	**Group**	**Estimated VO_{2max}**
2	Sedentary	26.9 ml/kg/min
4	Sedentary	16.5 ml/kg/min
5	Sedentary	26.1 ml/kg/min
1	Highly Fit	75.7 ml/kg/min
3	Highly Fit	57.5 ml/kg/min
7	Highly Fit	62.5 ml/kg/min
9	Highly Fit	53.0 ml/kg/min

Figure 5.3 shows examples of hand movement trajectories and CoP path of one participant from each group for the coupled and decoupled conditions. Note the similarities in hand movement trajectories and different endpoint errors between conditions (compare blue elliptical areas for endpoints of EH and EHR for each participant). However, CoP path appears similar between conditions and participants. Analyses verified no significant differences existed for CoP variables.

a Highly fit participant hand data



b Sedentary participant hand data



c CoP data for a highly fit participant, followed by a low fit participant

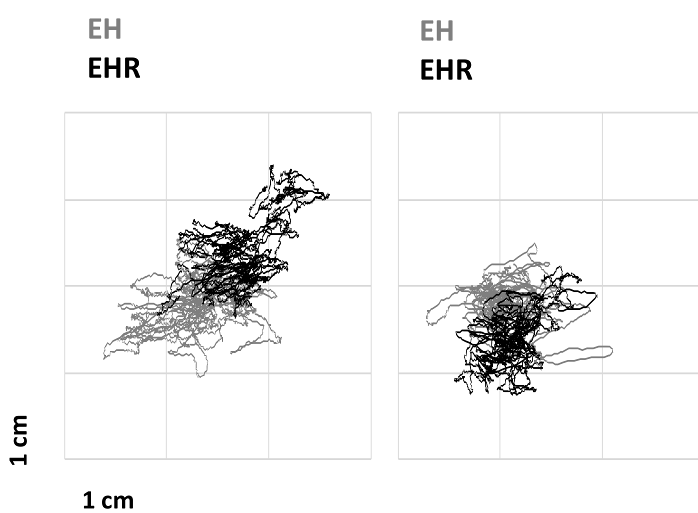


Figure 5.3. Hand and CoP data of the 2 conditions.
(caption cont.'d.)

EH/EHR hand data are shown for **a)** highly fit participant hand performance **b)** sedentary participant hand performance. CoP data are also shown for **c)** EH/EHR conditions for a highly fit participant (left panel), followed by a sedentary participant (right panel). The grey lines represent EH CoP paths, while the black lines represent EHR CoP paths.

Figure 5.4 shows an example of EEG data for all channels recorded during a pre-measure, EH, and EHR performances from one participant from the highly fit group. Note that activation of CP6 in EHR (Figure 5.4c) exceeded activations in EH (Figure 5.4b).

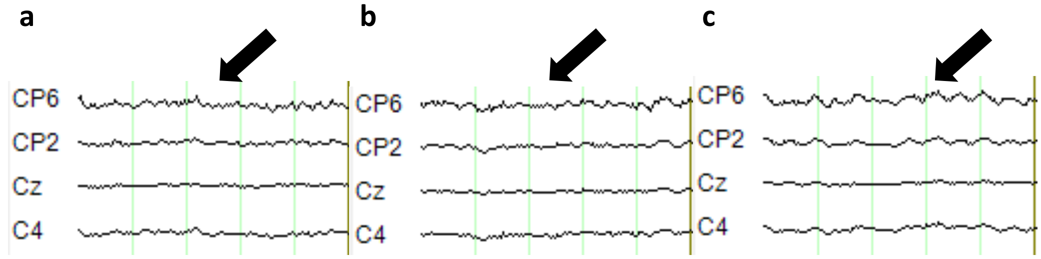


Figure 5.4 EEG data. EEG data are shown for **a)** eyes open (pre measure) **b)** EH condition **c)** EHR condition for one subject. The data represent EEG measures for multiple electrodes. The dark black arrows indicate CP6 activity during the corresponding trial performance.

Table 5.2 reveals the main results for hand variables separated by EEG and force plate data collections. Hand performance data for EEG trials and force plate trials were almost identical. AE (Figure 5.5a), RT (data not shown), and RespT (Figure 5.5b) were all greater in EHR compared to EH, while Condition effects for MT approached significance (Table 5.2). People took longer to react and perform the task with greater errors for decoupled movements of the eyes and hand. On the other hand PV of EH exceeded EHR only for force plate trials. No other significant differences in hand kinematics existed, thus mean data for spatial kinematics between groups follow data plots (Figure 5.3a-b).

Table 5.2 ANOVA Results

EEG data					Force Plate data				
Variable	**Effect**	**F-value (1,5)**	**P-value**	**Effect size**	**Variable**	**Effect**	**F-value (1,5)**	**P-value**	**Effect size**
RT	Group	2.32	0.19	0.32	RT	Group	0.51	0.51	0.09
	Condition	**8.92**	**0.03**	**0.64**		Condition	**19.91**	**0.01**	**0.80**
	Group x condition	0.80	0.41	0.14		Group x condition	0.60	0.47	0.11
MT	Group	0.48	0.52	0.09	MT	Group	0.01	0.92	0.00
	Condition	6.25	0.06	0.56		Condition	5.68	0.06	0.53
	Group x condition	0.42	0.55	0.08		Group x condition	0.05	0.84	0.01
PV	Group	0.47	0.53	0.09	PV	Group	0.00	0.99	0.00
	Condition	2.76	0.16	0.36		Condition	**11.06**	**0.02**	**0.69**
	Group x condition	0.14	0.73	0.03		Group x condition	0.31	0.60	0.06
RespT	Group	0.02	0.97	0.00	RespT	Group	0.13	0.73	0.03
	Condition	**11.42**	**0.02**	**0.70**		Condition	**11.08**	**0.02**	**0.69**
	Group x condition	0.09	0.78	0.02		Group x condition	0.17	0.70	0.03
AE	Group	1.96	0.22	0.28	AE	Group	0.01	0.93	0.00
	Condition	**10.48**	**0.02**	**0.68**		Condition	6.77	0.06	0.58
	Group x condition	0.47	0.52	0.09		Group x condition	0.42	0.55	0.08
aIDE	Group	0.55	0.49	0.10	aIDE	Group	0.04	0.84	0.01
	Condition	0.00	0.97	0.00		Condition	0.27	0.62	0.05
	Group x condition	5.93	0.06	0.54		Group x condition	3.88	0.11	0.44
PL	Group	0.48	0.52	0.09	PL	Group	2.30	0.19	0.31
	Condition	3.11	0.14	0.38		Condition	1.34	0.30	0.21
	Group x condition	0.00	0.99	0.00		Group x condition	1.04	0.35	0.17

Note: Bold text represents significant effect at alpha < .05. Red text represents effects approaching significance.

Main effects of Condition on CP6 for the alpha *(F* = 9.12, *ES* = 0.65 , *P* < 0.03*)* and beta *(F* = 6.77, *ES* = 0.58 , *P* = 0.06) spectral frequencies were observed in EEG data. Post-hoc analysis of the alpha spectral frequencies revealed greater activations for EHR compared to EH

conditions (Figure 5.5c), while those for beta spectral frequencies did not reach significance (Figure 5.5d).

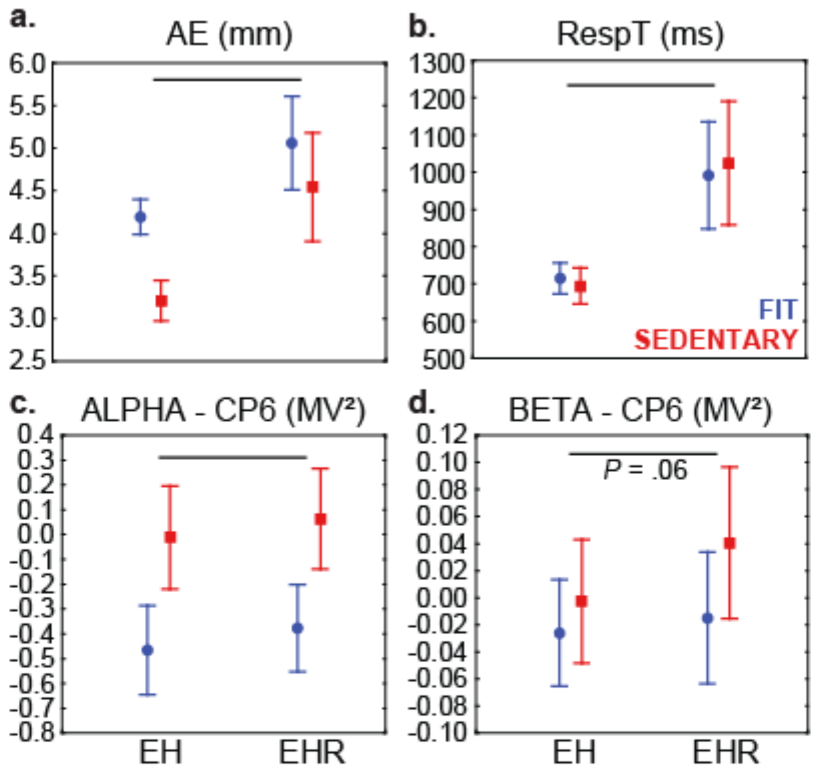


Figure 5.5 Plots of hand and EEG data. Mean values of hand data are shown for **a)** AE **b)** RespT. Mean values of EEG data are shown for **c)** alpha for CP6 **d)** beta for CP6. Blue circles represent means for the highly fit group, while red squares represent means for the sedentary group. Error bars represent standard errors. Black segments represent significant differences between tasks.

A similar non-significant main effect trend of Condition on CP6 for the theta spectral frequency (*P* = 0.07), on Cz for alpha spectral frequency (*P* = 0.06) and theta spectral frequency (*P* = 0.1), and on P4 for Beta spectral frequency (*P* = 0.10) also existed. In each case, there was a trend of increased activity in condition EHR compared to EH. A trending effect of Group was also observed of Cz for the alpha spectral frequency (*P* = 0.06) and revealed greater mean activation values for sedentary participants compared to highly fit participants. Also, a Group x Condition interaction trend was observed for electrode P4 for the beta spectral frequency (*P* =

0.05). Review of the mean data revealed greater activation in EHR compared to EH for the sedentary group with their between condition P4 differences exceeding those for the highly fit group. No other EEG differences were deemed significant/trending towards significance.

Discussion

In the current study, we investigated how performance during eye-hand coupling and decoupling tasks varied between highly fit and sedentary individuals while simultaneously recording cerebral activations or postural sway. Our results showed that reaching depended on task coupling/decoupling scenarios such that faster reaction times/completion speeds and greater accuracy existed for people performing the EH compared to the EHR conditions. As predicted, greater EEG activations existed for performances of the EHR compared to the EH conditions, although this was only significant for one electrode and frequency assessed. No group differences existed in variables of interest to support the corresponding fitness-related hypotheses that highly fit participants would perform faster and possibly with greater accuracy with greater cortical activation and less sway than their sedentary counterparts. The following text provides information on how these results complement the current literature.

Spatial Hand Measures

Decoupling the movements of the eyes and hand influences some spatial aspects of hand control. As expected, both groups of participants produced smaller absolute errors while performing eye-hand coupling tasks compared to decoupling tasks, and similar initial direction errors between tasks similar to elsewhere (Dalecki et al., 2016; Dalecki, Gorbet, & Sergio, 2019).

The between group similarities refute expectations of fitness and exercise level differences observed in previous work (Dupuy et al., 2015). The sedentary young adults used in

the present study did not experience performance deficits for the spatial planning of cognitively demanding motor skills when compared to the highly fit young adults. A potential explanation is that two of the three unfit participants reported high levels of sport-related eye-hand coordination experience when younger, which was in contrast to the highly fit group, where only one participant reported high levels of sport-related eye-hand coordination experience. Higher eye-hand coordination experience, known to improve movement accuracy (Southard, 2014), and strengthen fronto-parietal networks (Di et al., 2012), which contribute to spatial movement characteristics during similar eye-hand coordination tasks (Gorbet & Sergio, 2019), support this possibility.

Temporal Hand Measures

Temporal hand data results supported results of other studies, in terms of condition comparisons (Dalecki, Gorbet, & Sergio, 2019; Gorbet & Sergio, 2019; Salek et al., 2011). Specifically, participants could follow instructions for quickness and achieved faster RT, RespT, and MT and in some cases PV in EH compared to EHR conditions. Greater movement slowing during eye-hand decoupling trials, during the force plate testing, is possibly associated with increased cognitive effort needed to keep track of the cursor and finger (Feria, 2013).

The non-significant reaction times differences between highly fit and sedentary participants contradicts others which show fitness levels can influence performance during the incongruent portion of a Stroop task (Dupuy et al., 2015). We again reasoned that eye-hand coordination experience could account for the similarities between our participant groups, as improved hand speed is observed in athletes with greater eye-hand coordination experience (Neto, Magini, & Saba, 2007). Moreover, researchers, using the similar tasks to those in this

study, reported that youth individuals recovering from a concussion remedy eye-hand decoupling deficits if they have greater motor skill experience compared to less sports-experienced individuals (Dalecki, Gorbet, Macpherson, & Sergio, 2019). Together, the data provide support that eye-hand coordination experience can provide young adults with the expertise needed to achieve the speed and accuracy on the eye-hand decoupling tasks to overcome potential fitness related deficits.

Postural Sway

Results of the present study revealed no significant sway differences between eye-hand coupling conditions or groups while performing the tasks from an upright standing position. Thus, reductions in sway expected with eye-hand decoupling were not duplicated (Yeomans et al., 2020). We attributed these differences to methodological variations known to influence performances in other tasks. Remember that participants only performed one round of each task during force plate data collection after performing three rounds in the EEG data collection, due to force plate interference with EEG recordings. Similarities between conditions at the end of data collections may reflect the physical fatigue associated with increased sway (Barbieri et al., 2019; Gribble & Hertel, 2004; Yeomans et al., 2018). Similar sway reductions may also link to improvements in eye-hand coupling associated with task practice. People can reduce sway to help with performance of supra-postural tasks (Izquierdo-Herrera et al., 2018; Yeomans et al., 2018) that require greater attentional demands (Rey et al., 2008). However, the improved eye-hand coordination performance with practice, especially for the decoupling task (Dalecki, Usand, Van Gemmert, & Sergio, 2020), may accompany greater automation and less need for reductions in postural sway to control the attentional aspects of goal-directed reaching.

Evidence from similar sway observed between conditions of varying cognitive load (Stins, Michielsen, Roerdink, & Beek, 2009), supports this supposition. Improvements with practice may also explain the lack of support for the hypothesis associated with fitness based postural sway differences.

EEG Measures

We divided EEG measurements, obtained from selected electrodes, into pre-established frequency spectrums associated with functional control. Although many researchers use event related EEG measures during motor task performance to explore specific event related changes in neural activity, we averaged measures across rounds within a task to explore the potential of overall activation differences between the two tasks, similar to elsewhere (Beurskens et al., 2016). Therefore, some discussion in this section will be speculative in nature, when we utilize event related studies to help explain results found in the present study.

Greater alpha activations at CP6 electrode and with a trend at Cz electrode were observed during the EHR task compared to the EH task for both groups. In general, greater alpha activations explain the greater errors (Chung, Ofori, Misra, Hess, & Vaillancourt, 2017), as well as the greater need for movement preparation (Deiber et al., 2012) and selection (Benedek, Schickel, Jauk, Fink, & Neubauer, 2014), expected during the EHR task compared to the EH task for both groups. More specific greater event related alpha activity observed in areas CP6 and Cz relate to increased arousal and attention (Kim et al., 2017). Increased CP6 activations may also relate to increased working memory load during task performance in parietal areas (Hsieh, Ekstrom, & Ranganath, 2011) throughout performance of decoupled task trials. In EHR trials, participants likely required increased working memory load to prepare for

and select the appropriate movement because they needed to enact a cognitive-rule for movement decoupling multiple times throughout each round (Gorbet & Sergio, 2009). Our trending data for Cz alpha activations actually oppose those of Beurskens et al. 2016, who showed decreased Cz alpha activations during a dual processing task associated with increased cognitive demand. We observed the greater trend in Cz alpha activity for the more cognitively demanding task in our study. Differences between standing in our study compared to walking in their study may explain the differences observed but require further investigation to confirm.

A trending increase in beta wave amplitude at CP6 (centro-parietal electrode) for both groups and P4 (parietal electrode) for the sedentary group was observed during the decoupled condition compared to the coupled condition. Increased beta activation, in general, linked to better top-down control of attention related to improved performance during the incongruent portion of a Stroop task (Wang et al., 2019), which requires inhibitory responses similar to the decoupling task. Increased beta activation at CP6 linked to improved cognitive performance in humans (Kim et al., 2017), while increased P4 activations linked to visually guided reaching task in monkeys when compared to a resting state (MacKay & Mendonca, 1995). These trends support the common thought that the decoupling task requires greater cognitive demands (Dalecki et al., 2016; Dalecki, Gorbet, & Sergio, 2019) and that the sedentary group may use greater sensorimotor processing during the decoupled task compared to the coupled task.

Trending increases in theta activation observed at CP6 and Cz electrodes during EHR task performance compared to EH existed. Higher event related theta activations present with increased cognitive load in health individuals compared to individuals with cognitive impairment (Cummins, Broughton, & Finnigan, 2008). Theta activation increases for CP6

suggest a potential increase cognitive-load and/or multitasking need (Puma, Matton, Paubel, Raufaste, & El-Yagoubi, 2018), expected in decoupled task performances. Theta increases for Cz activation linked to improved response time performance (Fortunato et al., 2015) not observed here. Apparently, theta activation for moving as fast as possible (Fortunato et al., 2015) and moving as fast and as accurate as possible in our study differ.

Functional outcomes for multiple frequency activations can differ from independent frequency band outcomes. For example, the increased CP6 activations across alpha along with trends for beta and theta waves in the EHR compared to the EH task would associate with supra-marginal gyrus function related to somatosensory integration (Zhang, Chen, Hou, & Wu, 2019). These results support previous decoupling research describing greater parietal activations in the decoupled task compared to the coupled task using fMRI technology (Gorbet & Sergio, 2019). While the motor performance of the decoupling task is often associated with increased cognitive demands (Salek et al., 2011), cortical activations provide support that sensory integration differences between the two tasks may provide more information about the driving mechanism behind decoupling task performance.

Study limitations and Future Research

This study is not without limitations. The small sample size in each group does not provide strong power for the results observed or enable analyses between sexes. Future studies should utilize more participants to increase the statistical power. The EEG analysis was a major limitation in this study as well. Typically, EEG event related analyzes provide greater insight into activations associated with specific events and their associated function. We were unable to sync the EEG system and the cognitive-motor task program, so used a simple spontaneous

spectral analysis to provide some insight into cortical activation during task performances. Also, performing force plate trials separately after the trials with EEG was not ideal. Although signal interference limited our abilities in this regard, associated fatigue and/or learning effects possibly skewed the postural sway results in this study which diverged from others in the literature. Another limitation involved the study participants. We were not sure if the type of previous sport experience for participants would influence outcomes. We acknowledge that these differences likely influenced observed results. Once confirmed with further testing, it is also possible to assess whether eye-hand coordination experience, itself, can help mediate movement deficits in neurological/special populations (i.e., tai chi training for Parkinson's disease patients (Li et al., 2012)). We also consider the possibility that using a combination of exercise and/or sport performance to increase fitness levels and eye-hand coordination needed to improve sensorimotor performance with cognitive integration (Kioumourtzoglou, Derri, Mertzanidou, & Tzetzis, 1997). Future decoupling assessments typically used in neurological populations, could incorporate measures of cerebral activations to provide a more complete assessment during deterioration or recovery needed for the most effective treatment.

Conclusion

It appears that no eye-hand coordination differences existed between highly fit and sedentary individuals, and therefore sedentary individuals may not experience eye-hand coordination motor deficits during a cognitive-sensory-motor integration task as a result of poor aerobic fitness levels. We use the previous eye-hand sport-related experience to explain these similarities. The postural sway similarities between conditions likely resulted from mental/physical fatigue and practice effects which made postural control more automated.

Finally, different and trending cerebral activations between conditions related to the greater attentional and movement preparation/selection associated with sensorimotor processing during the decoupled task when compared to the coupled task. We concluded that reaching performance declines accompanied increased sensorimotor demands during eye-hand decoupling that may link to prior and current athletic experience and not fitness level. However, it is important to note that low participant numbers in this study may have attributed to lack of results found between participant groups. More research should be performed to verify or dispute the claims made regarding this research.

CHAPTER 6. CONCLUSIONS

The aim of this study was to expand the knowledge of control over eye-hand coupled and decoupled tasks. We investigated the influence of eye movement on the eye-hand coordination tasks, as well as how these tasks influence postural control or whether postural control could influence eye-hand coordination. We also studied whether sedentary populations have altered eye-hand coordination performance or cortical activations due to the cognitively demanding nature of the decoupled task when compared to highly fit individuals. Results were used to determine if eye movements could help explain previous performance differences observed in the literature, whether bidirectional control for eye-hand coordination and posture exist, and whether cerebral activation differences existed between tasks/populations.

Key Results

The first study (Chapter 3) was set-up to determine how various eye movements and/or visual fixations can alter eye-hand coordination performance during coupling and decoupling tasks. We investigated how these visual influences can alter both temporal (i.e., movement time) and spatial (i.e., endpoint error) measures. It appears that saccadic eye movements, thought to be the preferred eye movement when responding to visual stimuli (Song & McPeek, 2009), may be the preferred method to perform eye-hand coordination tasks as quickly as possible. Fixations may also improve temporal aspects of eye-hand coordination compared to smooth pursuit eye movements. However, smooth pursuit eye movements may improve spatial performance of these tasks, potentially due to their reduced peak speed and longer movement times. This idea is partially supported by Fitts' law, which shows a speed-accuracy trade-off (Fitts, 1954).. Therefore, similar to other aspects of motor control, like attenuating postural

control (Yeomans et al., 2018), eye movement selection significantly impacts eye-hand coordination performances.

The second study (Chapter 4) was designed to determine how eye-hand coupling and decoupling task performance changed from the sitting to standing position, and how the two eye-hand coordination tasks influence postural control while standing. While no differences were observed between sitting and standing for either task, the decoupled task attenuated sway compared to the coupled condition. Apparently, the increase in attentional resources from the motor system required to control posture for standing compared to sitting (Lajoie et al., 1993), did not negatively influence eye-hand coordination performance or improve accuracy, unlike other studies using a more constrained sitting position (Hondzinski & Kwon, 2009). We attributed the lower sway displacements for decoupling on the increased attentional demands associated with task performances (Rey et al., 2008), making it serve as a supra-postural task requiring greater postural control to help limit errors (Izquierdo-Herrera et al., 2018; Stoffregen et al., 2007; Yeomans et al., 2020; Yeomans et al., 2018).

The third study (Chapter 5), was designed to determine how performance during coupled and decoupled eye-hand coordination varies between highly fit and sedentary individuals. Secondary aims involved determining cerebral activation and postural sway differences between these groups and tasks. The lack of eye-hand coordination differences between groups contradicted other research showing differences between highly fit and sedentary groups (Dupuy et al., 2015; Themanson et al., 2008). Further review of participant background revealed previous athletic experience involving eye-hand coordination in the sedentary group (Neto et al., 2007) to potentially explain these differences. Increased cerebral

activations during decoupled task performances associated with greater sensorimotor demands and possibly cognitive-load, regardless of group. Sedentary groups also appeared to improve sensorimotor processing compared to highly fit individuals, possibly due to the aforementioned eye-hand coordination experience. Increased sensorimotor demands and possibly cognitive-motor interactions for motor planning and selection during eye-hand decoupling may link to prior and current athletic skills.

Comparison Across Studies

We used three experiments to study various influences on eye-hand coordination performances. In each study participants performed visuomotor tasks with different levels of eye-hand coordination which required varying levels of cognitive effort. In general, results supported previous findings, that decoupled task performances decreased spatial and temporal aspects of movement for participants told to move as quickly and accurately as possible (Dalecki et al., 2016; Dalecki, Gorbet, & Sergio, 2019). People maintained temporal and spatial declines associated with the performance of decoupling tasks for methodological changes.

Results from study 1 in the present manuscript provided evidence that type of eye movements used can influence performance of eye-hand coordination tasks. Thus, eye movements were also recorded in studies 2 and 3. Although participants in these studies typically used saccades toward targets, as observed previously. This suggest that saccades may the preferred eye movement of choice when performing goal-directed eye-hand coordination tasks (Song & McPeek, 2009).

We found evidence that the decoupled task may serve as a supra-postural task in comparison to the coupled task, due to attenuated sway (Izquierdo-Herrera et al., 2018;

Stoffregen et al., 2007; Yeomans et al., 2018) during this condition. However, there was a lack of postural sway differences between the two eye-hand coordination tasks in the third study, which is in contrast to results to the second study. One potential explanation for this discrepancy is the difference in the number of trials used to collect this force data in each study (i.e., two trials of force data in the second compared to one trial in third study). This could be suggesting that at least two trials of force data must be collected in order to adequately assess posture control while performing cognitively demanding tasks while standing. Another explanation could be that improvements in task performance in study 3, due to practice (Dalecki et al., 2020), altered findings between studies.

Summary

This research attempts to expand the knowledge related to eye-hand coordination performance. The first study provides evidence that eye movement selection significantly influences eye-hand coordination performance during coupled and decoupled tasks. The second study reveals that postural sway may be attenuated during the decoupled task. Decoupled performance continuously produced worse temporal and spatial performance as shown in previous work (Dalecki, Gorbet, Macpherson, et al., 2019; Gorbet & Sergio, 2019; Salek et al., 2011). The tasks also resulted in different postural sway/cerebral activations. These sway measure and cerebral activation differences may be associated with an increased cognitive demand of the decoupled task. However, it appears that eye-hand coordination deficits do not accompany a sedentary lifestyle for young healthy adults compared to a lifestyle of high fitness. Potentially, their previous athletic experience (Neto et al., 2007) involving good eye-hand coordination skills, which was observed in the participants in the sedentary group for

the third study, may have built a larger eye-hand coordination 'reserve' (Dalecki, Gorbet, Macpherson, et al., 2019) which compensated potential performance declines compared to highly fit individuals. Taken together, eye movements, cerebral activations, and athletic experience should be considered when determining differences between groups during eye-hand coordination tasks. Future experiments could be developed to assess the claims made in this document.

Future Directions

The first study revealed that singular eye movement selection led to altered eye-hand coordination performance. However, traditionally the eye-hand coordination tasks used in the study have previously not recorded eye movements during task performance (Dalecki et al., 2016; Dalecki, Gorbet, Macpherson, et al., 2019; Dalecki, Gorbet, & Sergio, 2019). Due to the nature of the tasks primary used in literature, showing altered cognitive-motor functioning for example in concussed populations (Dalecki et al., 2016), observing eye movements may provide additional helpful information to explain task performance differences between groups (i.e., due to altered eye functions after brain trauma). Therefore, it is suggested that in future when using these cognitive-motor integration tasks, eye movement instruction and/or eye tracking technology should be used, if possible, since it can provide further information to discriminate eye-hand coordination performance for concussed and healthy controls. This may be similar for other neurologic populations such as participants with dementia or mild-cognitive impairment (Hawkins & Sergio, 2014; Salek et al., 2011).

The second study revealed altered postural control during the eye-hand task with increased cognitive demands to suggest that the decoupled task may act as a supra-postural

task that can attenuate sway. However, in the third study we did not observe these same findings. Speculation as to why this occurred, includes the difference in trial sequence for potential learning effects and fatigue may explain these differences. Future research should investigate if the decoupled task actually attenuates sway. If so, investigators could determine whether the use of supra-postural tasks still attenuates sway in neurological populations with altered functional connectivity (Hawkins et al., 2015; Raichlen et al., 2016), known to have postural control detriments (Helmich, Berger, & Lausberg, 2016), to see if it is population dependent. Researchers could also investigate whether or not hand performance in the decoupled condition changes if the sway is manually manipulated to further alter attenuation demands.

The third study revealed altered cerebral activations between coupled and decoupled eye-hand coordination tasks, but no eye-hand coordination differences between sedentary and highly fit individuals. Since the understanding that sport-related eye-hand coordination strengthens fronto-parietal networks, and thus improves brain functions (Di et al., 2012), researchers should control for athletic experience and eye-hand coordination experience when investigating aerobic fitness's influence on eye-hand coordination performance, especially if the tasks incorporate cognitive-motor intergration.

APPENDIX A. IRB APPROVAL FORM

ACTION ON PROTOCOL APPROVAL REQUEST

Dr. Dennis Landin, Chair
130 David Boyd Hall
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P: 225.578.8692
F: 225.578.5983
irb@lsu.edu
lsu.edu/research

TO: Marc Dalecki
Kinesiology

FROM: Dennis Landin
Chair, Institutional Review Board

DATE: January 2, 2020

RE: **IRB#** 4062

TITLE: Cognitive-motor integration in young adult participants

New Protocol/Modification/Continuation: Modification

Brief Modification Description: Add Guillaume Spielmann to the study, look at cerebral oxygenation and/or activations during cognitive-motor task performance, using either near infrared spectroscopy and/or electroencephalogram technology, respectively; assess both sedentary and highly active young adults using this cognitive motor-task; add a physical fitness exam and a YMCA sub-maximal cycle ergometer test; collect blood samples from participants to measure brain derived neurotrophic factor in each group

Review type: Full ____ Expedited __X___ **Review date:** 12/11/2019

Risk Factor: Minimal ___X___ Uncertain __________ Greater Than Minimal_______

Approved___X____ **Disapproved** ___________

Approval Date: 1/2/2020 **Approval Expiration Date:** N/A

Re-review frequency: (annual unless otherwise stated)

Number of subjects approved: 100

LSU Proposal Number (if applicable):

By: Dennis Landin, Chairman DLandin

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING –
Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
7. Notification of the IRB of a serious compliance failure.
8. **SPECIAL NOTE: Make sure you use bcc when emailing more than one recipient.**

**All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb*

APPENDIX B. CONSENT FORM

CONSENT TO PARTICIPATE IN A RESEARCH STUDY INFORMED CONSENT

Study Title:
Cognitive-motor integration in young adult participants
Purpose of the Study and Study Procedures:
The purpose of this research project is to identify the control processes employed by the brain when interacting with one's environment. You will be asked to make simple point-to-point finger movements along a touchscreen in order to move a cursor to a target displayed on a computer monitor. We will be recording the position of your finger as you displace the cursor. To obtain these measures, we will ask you to move your finger along a touch sensitive screen. You may be asked to perform additional cognitive tasks, which could be a attention task and a sensory-cognitive interference task. Here, you press buttons on the keyboard in accordance to information displayed on a computer monitor. You may be standing or sitting during performances. We may record your eye movements via an eye tracker. There should be no discomfort or fatigue associated with these procedures as rest periods will be provided. We will also ask you to fill in different questionnaires linked to your demographic information, concussion and diabetes history, sport activity, handedness, and may ask in addition about your subjective task load throughout the experiment as well as your current mood. Your estimated participation time will be around 90 minutes or less and will depend on how many conditions you perform. You will be given breaks between conditions and when requested. You will also be asked to complete an IPAQ questionnaire, which will provide the researchers information about your physical activity levels.
Risks/Discomfort:
You may tire when standing; however, breaks between conditions and when requested should limit this possibility. There are no known additional risks associated with participation in the study.
Benefits:
There are no direct benefits from participation in the study. However, the information gained from this study will be used to gain insight into how the central nervous system coordinates movements when performing eye-hand coordination tasks under normal conditions.

Investigators:
If you have any questions regarding the study, please contact, Monday - Friday, 9:00am-5:00pm
Marc Dalecki, Ph.D. Phone: 225-578-6087; E-mail: mdalecki@lsu.edu,
Jan Hondzinski, Ph.D., Email: jhondz1@lsu.edu
Matthew Yeomans, graduate student, Email: myeoma1@lsu.edu
See student investigators below.

Performance Site:
School of Kinesiology, Sensoriomotor Laboratory (165 HPL)
Number of Subjects:

Overall, 20-100 participants will be recruited for this study.

Subjects:

Participants can be between the ages of 18 and 40 years. These participants can be left- or right-handed, and must be able to move their hands and fingers independently and have normal or corrected to normal vision (≤ 20/40 visual acuity). Participants will be excluded from the study if they are pregnant, or have any past/present musculoskeletal or neurological disorders that presently affect their upper limb movements.

Right to Refuse:

Participants may choose to not to participate or withdraw from the study at any time without any penalty whatsoever.

Financial Information:

You will receive no financial compensation for participating and you have no financial obligations as result of participation.

Privacy:

Every effort will be made to maintain the confidentiality of your study records. Results of the study may be published; however, we will keep your name and other identifying information private. Other than as set forth above, your identity will remain confidential unless disclosure is required by law.

Signatures:

The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. If I have questions about subjects' rights or other concerns, I can contact Dr. Dennis Landon, Chairman, LSU Institutional Review Board, (225)-578-8692, irb@lsu.edu, www.lsu.edu/irb. I agree to participate in the study described above and acknowledge the researchers' obligation to provide me with a copy of this consent form if signed by me.

I,__________________________________, agree to be in a study to understand how the brain controls movement. I will have to slide a finger or a pen to move a cursor across a touchscreen and to press keyboard buttons in accordance to targets presented on displays. I can decide to stop being in the study at any time without getting in trouble.

Subject Signature: _____________________________ Date: _______________

Student investigators: Hailey Gros

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