The contribution of peripheral visual information to visuospatial mapping prior to movement initiation

by

Laura Jane Williams

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Kinesiology

Waterloo, Ontario, Canada, 2013

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Laura J. Williams

Abstract

Compensatory balance reactions impose tight temporal constraints to motor responses employed to re–capture stability. Vision is particularly important for compensatory reach–to–grasp reactions as locations of hand hold targets have varying inherent features and locations in 3D space, requiring precise motor commands in order to successfully contact the target. Internalizing a representation of the surrounding environment by creating a visuospatial map is possible means of circumventing temporal lags associated with using online visual feedback when performing compensatory reactions. Hand hold targets are often located in the peripheral visual field. This suggests an importance of mapping from the peripheral visual field and further suggests mapping of peripherally located targets may require the allocation of attentional resources in order to correctly encode their location. The purpose of this thesis was to examine the contribution of peripheral vision and associated attentional requirements of visuospatial mapping for rapid upper limb movements. Study 1 was designed to examine the influence of mapping with peripheral vision for compensatory reach–to–grasp reactions, specifically the influence of timing and location of visual information. Study 2 was designed to examine the potential effect a secondary visual attention task would have on mapping peripheral located targets prior to movement initiation. Overall the results from these studies show support for the ability to map peripherally located targets with peripheral visual feedback, and suggest that this mapping may be an automatic process. Findings from this thesis provide a basic insight into the incorporation of peripheral visual information into intrinsic visuospatial maps that provides a framework for future experiments into the understanding of how visuospatial maps are incorporated into compensatory balance reactions.

Acknowledgements

Roger Staubach said "spectacular achievements are always preceded by unspectacular preparation." I think Roger is onto something. It is my belief that the pursuit of higher education through graduate research shares many attributes with professional football. We enter as rookies with eager anticipation and nervousness at the goals we will pursue over the forthcoming years. We leave as veterans all the wiser with both the factual knowledge we have gained from study and the practical knowledge we have gained through countless trial and error. We have teammates and coaches with whom we discuss plays and strategy. We practice our plays again and again until the stars align and that one perfect play occurs. Of course, that moment for a grad student is more likely to be along the lines of running through a full collection without a technical issue. We get knocked down, many, many a time, and get back up again. It is a long and grueling season with many highs and hopefully not too many lows. And while we do not get an oversized trophy or a championship ring, or a parade through the streets, I like to think we get the same feeling of accomplishment in the end. Maybe more so.

I wish to extend the utmost gratitude to my supervisor, Dr. William McIlroy, for taking a chance on an individual with absolutely no research experience. I greatly appreciate your patience, guidance, support, and your straightforward manner. I admire your approach to research and your ability to funnel a project into carefully thought out hypotheses without losing sight of the bigger picture. I one day hope to emulate your ability to rationalize theories and ideas into a few succinct sentences. I also am greatly appreciative to Dr. Richard Staines and Dr. Stephen Prentice for agreeing to be on my thesis committee and for their contributions and insights into my thesis work.

I have also had the privilege to work with many other graduate students and post doctoral fellows who have guided me along the way. Many thanks to Dr. Veronica Miyasike da Silva and Dr. David Bolton for their time and assistance in the formulation of ideas for my thesis work, discussion and for the practical and technological skills learned in the laboratory. To those who volunteered their time to participate in this thesis research, I am forever grateful. I appreciate the wisdom, advice and friendship from many individuals that I have met over the past few years, from within the neuroscience labs and beyond. My special thanks to Kit Beyer, Jon Thacker, Boyd Badiuk, Rupesh Patel, Kate Brown, and Kristin Marks. To my parents, I thank you for supporting my pursuit of higher education.

.

Table of Contents

List of Abbreviations

ANOVA   Analysis of Variance

APA   Anticipatory Postural Adjustment

APR   Automatic Postural Response

BOS   Base of Support

CNS   Central Nervous System

COM   Centre of Mass

CVF   Central Visual Field

DLPFC   Dorsolateral Prefrontal Cortex

EMG   Electromyography

EOG   Electrooculography

FFOV   Functional Field of View

IRED   Infrared Emitting Diode

LCD   Liquid Crystal Diode

PVF   Peripheral Visual Field

List of Figures

List of Tables

Chapter 1: Introduction

1.1 Background

The ability to produce immediate responses to a sudden, unexpected loss of balance is an important component of successful postural control. Out of necessity, balance recovery reactions are extremely rapid and have been demonstrated to be initiated within $80 - 100$ milliseconds (msec) after perturbation onset, a time frame which is approximately twice as fast as the initiation of rapid voluntary movements (Horak & Nashner, 1986; Horak et al., 1997; Maki & McIlroy, 1997; McIlroy & Maki, 1995). Factors that are both extrinsic and intrinsic to the individual must be incorporated into these rapid responses. Extrinsic properties include obstacles, support surface properties, characteristics of the perturbation and the spatial properties of features within the environment, while intrinsic properties include the initial state or configuration of the body when the perturbation was experienced (Maisson, 1992; Maki & McIlroy, 2005). Neurological impairments that result in motor and / or cognitive dysfunction are also intrinsic factors that can affect balance control responses (Horak et al., 1997; Jacobs & Horak, 2007).

There is an extensive body of research examining the importance of visual information regarding the environmental surround in guiding volitional movements such as locomotion and reach–to–grasp. However, the temporal constraints associated with compensatory balance reactions may limit the ability to incorporate visual information into the initial phase of the recovery response (Ghafouri et al., 2004; King et al., 2011; Zettel et al., 2005). A possible control mechanism that has been suggested for overcoming such constraints is to create an intrinsic visuospatial map of the surrounding environment prior to the onset of perturbation (Ghafouri et al., 2004; Zettel et al., 2005, 2007). While the literature does support such a notion

there are still many questions regarding central nervous system (CNS) mechanisms underlying

the mapping process. Presumably visuospatial mapping is an automatic process that incorporates

incoming visual information regarding environmental features from both the central and

peripheral visual fields. Existing research focused on visual contributions to balance control

often considers only the central visual field or does not distinguish between mapping and online

visual feedback. Therefore, the objective of this thesis is to examine the ability of individuals to

create and act upon a representation of the visual environment created from peripheral visual

information for the purposes of guiding the control of rapid upper limb movements such as those

required for balance recovery.

Chapter 2: Literature Review

2.1 Postural Control

Postural stability affords us the independence to interact with our environment and participate in activities of daily living. Therefore, it is imperative that we are able coordinate postural control under a variety of circumstances. The musculoskeletal system acts to counterbalance forces imposed on the body by both internal constraints, such as limb configuration, and external constraints such as gravitational force (Frank & Earl, 1990; Horak, 1987; Massion, 1992; Mergner & Rosemeier, 1998). The ability to achieve postural equilibrium requires sensorimotor integration within the neuromuscular system to maintain the centre of mass (COM) within the base of support (BOS) of the body (Bouisset & Do, 2008; Horak, 2006; Maki & McIlroy, 1997, 2005; Maki et al., 2003; Patla, 2003).

Postural control can be viewed as a dichotomy of both static and dynamic parameters that are used to maintain equilibrium (Bouisset & Do, 2008; Maki & McIlroy, 2005). Static balance control refers to the maintenance of a stationary postural configuration, such as quiet stance or sitting, while dynamic balance control requires that stability be maintained during an ongoing movement (Bouisett & Do, 2008). Two categories of responses that occur in order to maintain postural equilibrium for both static and dynamic balance control are known as anticipatory postural adjustments (APAs) and automatic postural reactions (APRs) (Frank & Earl, 1990; Massion, 1992). Anticipatory postural adjustments are utilized under volitional movement conditions or conditions where a perturbation is expected and the individual has time to prepare a response (Maki & McIlroy, 2005; McIlroy & Maki, 1993). For a given body position, the muscles that are responsible for maintaining postural control will activate prior to the onset of activity in the muscles required to complete a volitional movement (Massion, 1992; Maki &

McIlroy, 2005). These feed forward responses are believed to occur as a means of minimizing disturbances to postural equilibrium that result from the movement of interest (Maisson, 1992; McIlroy & Maki, 1993).Conversely, APRs are used when the postural disturbance is unexpected and cannot be planned for. When faced with unexpected perturbation forces, automatic postural reactions are the mechanism by which balance is maintained (Patla, 2003).

Automatic postural reactions are not generalizable startle responses, but rather are highly specific to the characteristics of the stimulus and task conditions. These responses have been demonstrated to be modifiable based on the following parameters: 1) perturbation characteristics (velocity, direction, and predictability), 2) pre – perturbation neuromotor state (previous experience, expectation, and arousal), 3) concurrent motor and / or cognitive activity and 4) environmental context(s) such as obstacles and support surface characteristics (Jacobs & Horak, 2007; Maki & McIlroy, 2007; Patla, 2003; Zettel et al., 2005).

2.2 Types of Balance Control Reactions

The objective of the automatic postural reactions is to rapidly activate appropriate muscle sequences in order to generate stabilizing forces against a support surface so as to counteract the destabilizing force(s) of the perturbation (Horak et al., 1997; Jacobs & Horak, 2007). Automatic postural reactions can be further subdivided into two distinct categories of general strategies that individuals employ in order to maintain postural equilibrium: fixed support and change in support reactions.

2.2.1 Fixed Support Reactions

Fixed support reactions identify a class of compensatory balance reactions in which the BOS remains unaltered in response to a perturbation (Maki & McIlroy, 1997, 2006). This response is sufficient for perturbations that are delivered at a slow velocity and small magnitudes of force

(Horak, 1987). To counteract a destabilizing force, the CNS activates muscles to produce counterbalancing torque at the articulation(s) responsible for arresting the motion of the body and maintaining the COM within the current BOS (Horak et al., 1997; Mergner & Rosemeier, 1998). In a standing posture, muscle torque will be generated at the ankles, hips and lumbar spine (Maki et al., 2003). Two common strategies employed in fixed support reactions include the ankle strategy and the hip strategy, such that individuals will initiate flexion and / or extension movements at the respective articulations so as to stabilize the COM (Horak, 1987). However, increasing perturbation forces results in a corresponding increase in the velocity of the COM. When this occurs, fixed support reactions will no longer be able to arrest the whole body motion induced by the perturbation and individuals must adopt a different strategy, the change in support reaction, to regain stability (Maki et al., 1997, 2003).

2.2.2 Change in Support Reactions

Change in support reactions involve movement of the lower limbs (stepping) and / or upper limbs (reach–to–grasp) in order to increase the BOS to recapture the COM and arrest whole body motion (Horak, 1987; Maki & McIlroy, 1997, 2005). While change in support reactions have been observed when individuals experience small perturbation forces (such that a fixed support strategy would successfully recapture stability), they are the only sufficient strategy that will be able to recapture stability in response to large perturbation forces (Maki & McIlroy, 2005; Maki et al., 2003). The central control of these rapid reactions initiated in order to arrest the movement is remarkably sophisticated. It requires the response to be initiated in the appropriate direction with respect to the direction of the perturbation, compensation for concurrently occurring body motion (e.g. locomotion) as well as environmental constraints that may restrict preferred limb trajectories for stepping and / or reaching (Maki et al., 2003; Zettel et al., 2005). These responses

must also include parameters associated with the support surface as well as the initial configuration of the limbs at the time of perturbation onset (Horak, 1987). As previously mentioned, perturbation induced stepping responses are highly modifiable with respect to perturbation and environmental characteristics. Recently, the upper limb has also received attention with respect to balance control. McIlroy & Maki (1995) demonstrated that upper limb responses are also adapted to meet perturbation and environmental characteristics. Upper limb responses provide unique insight into the CNS regulation of compensatory balance. The arms do not provide direct body support in most postures and therefore do not experience the initial loading of sensory receptors that would provide the CNS with the initial somatosensory characteristics of the perturbation (McIlroy & Maki, 1995). However, upper limb responses are initiated at similar speeds to those of lower limb responses when individuals receive perturbations in a standing posture (Gage et al., 2007; Maki & McIlroy, 1997; McIlroy & Maki, 1995).

Due to the complexity and intricacy of the movements associated with change in support reactions with respect to the environment, there is debate regarding the involvement of higher cortical areas in the execution of such reactions. Rapidly evoked balance reactions have traditionally been considered to be controlled by the brainstem and spinal cord under the pretense that cortical involvement would lead to temporal delays in response initiation which in turn would be detrimental to effective re–stabilization (Jacobs & Horak, 2007; Maki & McIlroy, 2007). However, recent literature suggests that there is the potential for modification of rapid balance reactions from descending cortical commands despite the rapid latency of response initiation. In most cases while concurrently performing a postural maintenance task and a cognitive task, it is the cognitive task that incurs deficits in performance, presumably to prioritize

postural stability (Brown et al., 2002; Maki & McIlroy, 2007; Zettel et al., 2008). Decrements in cognitive task performance are used to infer that executive function is required for the maintenance of postural stability. It is also possible that the initial phases of balance recovery reactions are mediated at the level of the brainstem and spinal cord, and that descending cortical commands come into play in the later phases of the response which constitute the actual re – stabilization of the body (Jacobs & Horak, 2007; Zettel et al., 2005).

2.3 Sensory Components of Change in Support Reactions

Visual, vestibular and proprioceptive sensory feedback is crucial for the initiation of compensatory movements. Sensory feedback from these systems provides the CNS with information regarding postural configuration (seated vs. standing), dynamic activity associated with the posture / movement (quiet stance vs. locomotion) as well as the characteristics of the perturbation, all of which are vital factors that must be incorporated into a compensatory balance reaction (Frank & Earl, 1990; Inglis et al., 1994; Lephart et al., 1998; Wade & Jones, 1997).

Musculoskeletal and joint receptors relay afferent information regarding articular position, velocity and acceleration (Inglis et al., 1994; Lephart et al., 1998; Mergner & Rosemeier, 1998). This information is critical as somatosensory feedback regarding perturbation characteristics is vital for scaling the amplitude of the response as well as controlling any ongoing limb motion and the initiation and coordination of restorative limb movement. The vestibular system is particularly important for maintaining postural equilibrium with respect to gravitational forces in order to orient the head and trunk to the vertical axis of the support surface to enable spatial orientation based on a gaze centered reference frame (Horak, 2010). This becomes particularly important in our ability to distinguish between head & neck on trunk movements versus head & neck motion that is also accompanied by whole body movement (Horak, 2010). The importance

of head and trunk stabilization arises from our anatomical configuration: the head contains the

visual system and its receptors in its entirety while the COM is located within the trunk of the

individual (Horak, 2010; Mergner & Rosemeier, 1998).

2.3.1 Vision

Vision is an integral sensory component for maintaining balance. Visual feedback provides

the CNS with continually updated information regarding body position, egocentric spatial

awareness and the allocentric spatial location of objects within the environment (Black & Wood,

2005; Lord, 2006). Visual information regarding allocentric spatial features of the surrounding

environment is integral to enabling appropriate movements and navigation within that

environment (Baldauf & Deubel, 2010; Patla, 2003; Zettel et al., 2005). This is especially true

when rapid limb responses induced by a perturbation are required to occur within that immediate

environment. Not only is the acquisition of visuospatial information important, but the location

within the visual field (the central visual field (CVF) or the peripheral visual field (PVF)), the

incoming visuospatial information emanates from may also be of importance as central and

peripheral vision have different roles for the purposes of processing visual information (Berencsi

et al., 2005; Wade & Jones, 1997).

2.4 Contributions of Central and Peripheral Vision

In this thesis, central vision will be defined visual information that is perceived by the macula

and peripheral vision will be the remainder of the retina beyond that of the macula. The macula

is the central area of the retina that contains a high density of cone photoreceptors (Leff, 2004).

The fovea, which provides the greatest visual acuity, is located at the centre of the macula

(Tovee, 1996). Macular vision accounts for approximately the central 10 degrees of our visual

field and foveal vision the central 2 degrees (Piponnier et al., 2009; Sung & Chuang, 2010; Tovee, 1996).

Central vision allows for colour vision, object recognition and identification, fine detail discrimination, feature extraction, contrast sensitivity and the ability to distinguish the edges of objects within the environment (Frey et al., 2010; Sung & Chuang, 2010; Tovee, 1996; Wade & Jones, 1997). High visual acuity is achieved by having a low convergence ratio: the ratio of photoreceptor cells synapsing onto the retinal ganglion cells (Tovee, 1996). Central vision has a convergence ratio of one cone photoreceptor to one retinal ganglion cell (Sung & Chuang, 2010; Tovee, 1996). Damage to the macula through injury or disease (such as macular degeneration) may lead to a forced reliance on visuospatial information gathered from the peripheral visual field to allow for environmental interaction.

As visual eccentricity increases to the peripheral surface of the retina, the density of photoreceptor type changes from cones to rods (Sung & Chuang, 2010; Tovee, 1996). Unlike cones, rods provide low acuity, monochrome vision as the convergence ratio increases with increasing visual eccentricity (Sung & Chuang, 2010; Tovee, 1996). However, peripheral vision is important for interpreting observer motion including upper and lower limb movement, postural orientation of the individual and object perception (especially depth perception) in the environment (Alfano & Michel, 1990; Turano et al., 2005; Wade & Jones, 1997).

2.5 Vision and Voluntary Reaching

Reaching to grasp an object is a motor action used on a daily basis to interact with objects in the environment. In order for successful interaction, the CNS must be able to accurately perceive features inherent to the object, such as shape, size, orientation, and the spatial location of the object with respect to the individual (Gonzalez – Alvarez et al., 2007; Singhal et al., 2007;

Sivak & MacKenzie, 1990). Other contextual features of the object may also be of importance, such as its mass and / or potential fragility (for example an antique vase as opposed to a plastic cup) so that the appropriate amount of force can be used to manipulate it. An important contextual feature of compensatory reach–to–grasp movements may also include the context of the potential stability the object may provide should it be grabbed (i.e. if the object is fixed and sturdy such as a hand railing vs. an object that is unstable and freely moved) (Baldauf & Deubel, 2010; Schlicht & Schrater, 2007).

Visual feedback increases accuracy when executing prehensile and pointing movements. The availability of visual information with respect to both the hand and the target produce the most accurate movements as compared to vision of one alone or when vision is absent (King et al., 2011; Sivak & MacKenzie, 1990). Also, visual feedback of the hand and target during the later stage of movement and target acquirement will result in more accurate pointing and grasping movements as both the hand and the object are brought into foveal capture (Baldauf & Deubel, 2010; Land, 2009; Paillard, 1995; Sivak & MacKenzie, 1990). During natural reaching movements, the CNS utilizes incoming information from both visual fields to guide motor action(s) to produce accurate movements (Sivak & MacKenzie, 1990). The central visual field provides information regarding intrinsic object features which are important for the motor control of the limb for both the transport and grasping components of prehensile movements (Sivak & MacKenzie, 1990). The peripheral visual field provides information regarding environmental features as well as information regarding limb motion to guide the upper limb through the transport phase in order to bring the hand towards the target (Paillard, 1995; Sivak & MacKenzie, 1990).

Land (2009) posits that visually guided behaviour is controlled by four main cortical areas that are essentially sub–systems for successful neuromotor integration. He states that the internal representation of the task is controlled by the dorsolateral prefrontal cortex (DLPFC). This may be considered to be analogous to executive function requirements that are used to allocate attention to the current task. Attention requirements appear to arise based on the environment in which the individual is required to interact. In order to carry out the goal directed behaviour of a successful reach–to–grasp movement, the individual must maintain in memory the features of the target object as well as areas in the visual field that have already been scanned during the visual search for that object (Sengpiel & Hubener, 1999). This must then be incorporated into the planning and execution of the movement to enable the appropriate motor synergies and produce a coordinated action (Baldauf & Deubel, 2010; Land, 2009). The DLPFC then relays information to the appropriate subsystems: the "gaze system" composed of the frontal eye fields and lateral intraparietal area for the control and execution of saccades; the "visual system" composed of the occipital and temporal lobes for the processing of visual stimuli; and the "motor system" composed of the premotor and primary motor cortices as well as the area of the parietal cortex responsible for coordinating incoming sensory information regarding the execution of the movement (Land, 2009, pg. 52).

These neuroanatomical areas are similar to that of another visual processing theory present in the literature which suggests that prehension movements are controlled through two independent, yet highly interconnected cortical streams: the dorsal and ventral streams (Goodale & Milner, 1992). Visual inputs are initially processed in the primary visual cortex and then projected to other cortical areas through the two cortical streams for further processing (Gonzalez-Alvarez et al., 2007). The dorsal visual stream projects from the primary visual cortex

to the posterior parietal cortex and is considered the "where" stream; it is responsible for determining spatial location of objects and therefore is speculated to regulate visually guided movements (Gonzalez-Alvarez et al., 2007; Singhal et al., 2007). Conversely, the ventral visual stream projects from the primary visual cortex to the inferotemporal cortex and is considered the "what" stream; it is responsible for correctly identifying the object (Gonzalez-Alvarez et al., 2007). The ventral visual stream is speculated to be important for storing a representation of the object for future recall, a process that may be a component of visuospatial map construction (Gonzalez-Alvarez et al., 2007).

2.6 Central Nervous System Framework for Visuospatial Mapping

Incoming visual information is initially encoded in a retinotopic reference frame (Hall & Colby, 2011; Thompson & Henriques, 2011). Mapping the visual scene in a retinotopic reference frame provides visual stability across saccades and eye blinks. This visual stability is achieved by corollary discharge regarding an upcoming saccade based on the intent to move the eyes to a new visual target area (Duhamel et al., 1992; Hall & Colby, 2011; Wurtz, 2008). This retinotopic updating transfers the encoding of visual information from neurons in the current receptive field to the neurons that will make up the future receptive field once the saccade has been executed (Duhamel et al., 1992; Hall & Colby, 2011; Wurtz, 2008). Cortical areas that have been implicated in retinotopic mapping include the visual cortices, the lateral intraparietal area, the frontal eye field and the superior colliculus (Colby & Hall, 2011; Thompson & Henriques, 2011).

The visual mapping of the environment in retinotopic coordinates then undergoes a visuomotor reference frame transformation in order to guide motor action (Binsted et al., 2006). These reference frames include head–centered, limb–centered, or body–centered coordinates

(Binsted et al., 2006; Thompson & Henriques, 2011). Kravitz and et al., (2011) propose that the occipito–parietal network transforms visual information from a retinotopic reference frame into the aforementioned egocentric reference frames and that these egocentric maps are used to convey the visuospatial information into the dorsal visual stream. The authors further suggest that the dorsal visual stream may be broken down into three sub streams which provide a framework for processing spatial working memory (supported by the parietal–prefrontal pathway), visually guided actions (supported by the parietal–premotor pathway) and spatial navigation (supported by the parietal–medial temporal pathway) (Kravitz et al., 2011).

The aforementioned cortical areas that are active in visuospatial processing are also the cortical areas that are highly active in the visual control of volitional reaching movements. It is likely that the visuospatial information of behaviourally relevant items within the immediate environment is updated on a moment to moment basis to enable the individual to have the most updated representation of object(s) with respect to egocentric space (Westwood et al., 2003). It has also been suggested that the egocentric reference frame regarding the spatial location of action relevant objects is not transformed from a visuospatial representation to a motor command until the decision has been made to initiate a movement towards an object so that the most recent visuospatial map can be utilized in the visuomotor transformation (Westwood et al., 2003).

2.7 Visual Information and Balance Control

Vision has been demonstrated to be an integral means for enabling human interaction with the environment. Specifically, visuospatial information regarding environmental features is imperative for guiding limb trajectory (reach–to–grasp and / or stepping) in temporally urgent situations (Lakhani et al., 2011). However, due to the temporal constraints associated with compensatory balance reactions, it may not be possible to use online visual feedback from the

13

CVF, as the delays associated with generating a saccade to a target area to bring it into central vision, feature extract any relevant information and then act upon said information would cause too much of a delay in initiating a response that would successfully restore balance (King et al., 2010). As a result, research has examined gaze behaviour and vision in both upper limb and lower limb balance control studies.

2.7.1 Vision and Compensatory Stepping

Various studies have examined vision and compensatory stepping and have found that fixations and / or gaze shifts to potential step landing sites are not required to successfully execute a step in response to a perturbation (Zettel et al 2005, 2007, 2008). This is true even when the imposed demands on the participants are high. For example, Zettel et al. (2005) examined gaze behaviour and compensatory stepping in a complex environment while subjects performed a concurrent attention demanding task. Participants performed perturbation induced stepping to a targeted area and / or avoided an obstacle, all while performing a visuomotor tracking task. These results are similar to studies examining gaze behaviour and obstacle avoidance during locomotion. Patla & Vickers (1997) found that subjects would fixate on an obstacle during the approach phase and step landing phase once the obstacle had been cleared, but would not fixate on the obstacle during the actual step clearance phase. Similarly, Marigold et al., (2007) found that subjects could successfully avoid obstacles that appeared suddenly in the walking path of participants without redirecting gaze at the object to bring it into central vision. Both of these studies demonstrate the importance of precursory visuospatial information and continuous visual feedback from the lower peripheral visual field for obstacle avoidance in locomotion studies, and it may be reasonable to assume that these two mechanisms are equally important in compensatory stepping and reaching.

2.7.2 Vision and Compensatory Reaching

Arguably, reach–to–grasp responses initiated as a result of unexpected perturbation forces impose greater control challenges with respect to recapturing stability than compensatory stepping. The characteristics of the support surface for the lower limbs has a high probability of remaining planar and predictable, with exceptions such as ramps and stairs, for execution of compensatory stepping reactions (Maki & McIlroy, 1997). Conversely, in reach–to–grasp reactions, potential hand holds are not always readily available, and when they are available, their spatial characteristics remain fixed in allocentric space within the environment while their egocentric location changes on an instantaneous basis as the individual incurs a fall (Cheng et al., 2009).

King et al. (2010) specifically examined peripherally guided compensatory reach–to–grasp reactions and found that subjects were able to successfully regain stability even when the handhold was small and its final location prior to perturbation was unpredictable. This was true even when the final handle location was at a 40 degree visual eccentricity; albeit kinematic differences occurred with the handle at this location as compared to the 20 and 30 degree handle locations. The same research group also examined gaze behaviour of participants as they navigated through a "natural" environmental setting. The authors concluded that, for the participants who made successful compensatory reach–to–grasp responses, initial arm trajectory towards the railing was guided by stored visuospatial information gathered separately from the central or peripheral visual fields and / or was directed by online peripheral visual feedback as none of the participants brought the handrail into the CVF prior to the initiation of the compensatory arm movement (King et al., 2011). Ghafouri et al., (2004) found that initial wrist trajectory was specific to the direction of perturbation and that this was true when vision was

occluded prior to perturbation onset, forcing participants to rely on a stored visuospatial map as no online visual feedback was available. The ability of participants to successfully grasp a stabilizing handle in these experiments demonstrates that visuospatial information gathered prior to perturbation and / or gathered from the visual periphery can be incorporated into compensatory reach–to–grasp reactions.

2.8 Rationale

The ability to maintain postural control is not only important for producing a desired, goal directed movement but is also important for responding to postural perturbations (Horak et al., 1997). The high incidence of falls in individuals with neuromuscular dysfunction is considered to occur as a result of incorrect postural responses generated by the central nervous system in response to a perturbation (Horak et al., 1997). Understanding the visual and cognitive requirements in controlling such rapid reactions in young, healthy individuals may provide greater insight into the nervous regulation of compensatory balance. Such knowledge may be valuable for the design of fall prevention programs as well as rehabilitation programs for those who have sustained neurologic injury. The studies included in this thesis are intended to examine the contribution of peripheral visual information and associated attentional requirements in the formation of an intrinsic visuospatial map for the purposes of immediate action.

2.9 Research Questions and Objectives

This thesis is comprised of two studies designed to address the following research objectives:

Study 1: Mapping with peripheral vision for compensatory reaching

- Examine the influence of *when* visual information regarding target location is acquired with respect to perturbation onset

- Examine the influence of *where* in the visual field (central versus peripheral) such visuospatial information is acquired from

Study 2: Dual task interference and mapping peripherally located targets

- Examine the potential effects of a secondary visual attention task on the ability to encode peripherally located targets prior to movement initiation

Chapter 3: Study 1

Can we use peripheral visual information to create a visuospatial map for use in rapid reach–to–grasp reactions?

3.1 Introduction

Unexpected perturbation forces that threaten postural stability initiate elegant compensatory reactions that aim to arrest whole body motion and recapture stability. These reactions are distinguished by their rapid initiation and execution as well as their appropriate accommodation to the constraints of the surrounding environment (Maki & McIlroy, 2006). In response to perturbations, compensatory stepping and / or reaching reactions are often used to alter the base of support (BOS) so as to recapture the center of mass (COM) within its limits of stability (Bouisset & Do, 2008; Maki & McIlroy, 1997, 2006) and are therefore referred to as change in support reactions (Maki & McIlroy, 1997, 2006). Unlike fixed support reactions where the limbs do not move to establish a new base of support, these change in support reactions must address the control challenges linked to the direction and amplitude of perturbation as well as the spatial characteristics of the environment since the new support surface may be complex (e.g. stairs, handrails) (Gage et al., 2007; Maki et al., 2003; Scovil et al., 2008; Zettel et al., 2005). Change in support reactions of the upper limb are most often challenged by complex three dimensional spatial surrounds demanding precise motor commands to achieve contact with the support surface (Cheng et al., 2009; Gage et al., 2007; Maki & McIlroy, 1997). For example, potential support targets for the upper limb, such as handrails, have different egocentric spatial locations, orientations and size characteristics in various environments. Remarkably, the CNS is able to generate appropriate responses with respect to perturbation characteristics and environmental constraints *after* the onset of the perturbation and

18

prior to the initiation of a response, a time frame which has been revealed to be as short as 80 –

100 msec (Horak & Nashner, 1986; Horak et al., 1997; McIlroy & Maki, 1995). In addition,

these rapid onset responses are also target specific (McIlroy & Maki, 1995) reinforcing the

notion that the spatial representation of possible targets was incorporated into the initial reach

trajectory (Ghafouri et al., 2004). How then, does the CNS achieve such rapid and adaptable

control to acquire and use visuospatial information to guide reach kinematics under such

temporal constraints?

There are two main strategies that may be utilized. One strategy is the use of online visual

feedback during the reach–to–grasp response that would begin after the onset of perturbation.

However, there are potential limitations to this strategy. Delays associated with acquiring and

processing visuospaital information post perturbation may result in delays in response initiation

and / or execution which have potential detrimental effects to the individual (Maki & McIlroy,

2005). A second approach is to acquire and transiently store a visual representation of the

immediate environment and to execute a rapid balance response based on this stored visuospatial

representation or "visuospatial map" (Ghafouri et al., 2004; Scovil et al., 2008).   The limitation

of this approach is that this visuospatial map would require continuous updating as balance

disturbances that occur in daily life are temporally unpredictable. In spite of this challenge,

recent studies have supported this strategy as a most likely approach to achieve the rapid

initiation and execution speeds of these reactions in order to successfully recapture stability

(Ghafouri et al., 2004; Scovil et al., 2008; Zettel et al., 2005, 2007). The strategy of acquiring

visual information before the onset of any perturbation (continuously mapping) has two main

advantages for decreasing central processing requirements post perturbation: 1) the elimination

of potential delays associated with the need to outline and execute visual saccades and / or head

& neck rotational movements towards the target and 2) decrease the need to incorporate online visual information into the creation and execution of the initial phases of the unique motor program (King et al., 2010, 2011; Zettel et al., 2005). Zettel et al., (2007) used a translating platform equipped with moving obstacles to induce compensatory stepping reactions in both younger and older adults. Their results demonstrated that both age groups were able to select the appropriate stepping limb for obstacle avoidance and both groups were able to do so without visually fixating on the obstacles, step landing site or the swing foot itself (Zettel et al., 2007). Reinforcing early work by McIlroy and Maki (1995), Ghafouri et al., (2004) specifically examined visuospatial mapping in compensatory reach–to–grasp reactions by comparing task conditions of occluding vision prior to perturbation onset with no visual occlusion. They found that initial wrist trajectories were not generic in response to the perturbation, but rather were dictated by the location of the target and the direction of the perturbation rather than the visual task condition (Ghafouri et al., 2004). These studies demonstrate that in the event of an unexpected postural disturbance, the CNS may utilize a pre–formed visuospatial map of the external surround along with sensory inputs regarding body motion in an attempt to recapture stability.

An additionally important question regarding the acquisition of visual information for the control of rapid reactions is where the visuospatial information is being acquired from: the central or peripheral field of view. If visual information is gathered after the onset of perturbation then saccade latencies associated with bringing potential targets into central vision may also increase time requirements necessary to acquire and utilize online visuospatial information. In contrast, if visual information is captured prior to perturbation (e.g. to continuously update a visuospatial map) then the reliance of central vision while moving though

natural environments would require constant redirection of gaze to potential targets or obstacles (King et al., 2011). While central vision is associated with high visual acuity to allow for detailed feature extraction, often times potential handhold targets such as railings are located in our peripheral field of view. Recent studies have revealed that even in complex tasks, such as approaching and navigating stairs, individuals do not direct central vision to handrails or even the stairs themselves (Miyasike – daSilva et al., 2011) Collectively this leads us to speculate that visuospatial mapping from the peripheral visual field may have a very prominent / beneficial role in pre–perturbation planning.

Studies examining volitional pointing, reaching, and grasping have found that when such movements are performed into the PVF there is reduced end point accuracy. However, reduced accuracy of perturbation evoked reach–to–grasp reactions pose more severe consequences, as failure to successfully anchor the upper limb to the handhold may result in a fall. King et al., (2010) examined potential speed-accuracy trade-offs with peripherally guided, perturbation evoked reach–to–grasp reactions. They found that participants were highly successful at recapturing stability regardless of the visual eccentricity of the handhold and that spatial information provided from peripheral vision (to a maximum visual angle of 40 degrees) was sufficient enough for participants to execute accurate reaches to a designated area of the target (King et al., 2010). While this study supports the role of peripheral vision in the control of compensatory reach to grasp reactions, it is difficult to distinguish the contribution of precursory visual information and online visuospatial control of reach trajectory.

The objective of this study was to examine two factors that are likely essential in the control of compensatory reach–to–grasp reactions: *when* visual information regarding target location is acquired (in this case, relative to the timing of perturbation) and *where* in the visual

field, (central or peripheral) the visual information is acquired from. The main hypothesis regarding *when* visual information is acquired was that the initial phase of the reach would be guided by the visuospatial information acquired prior to perturbation. This would be supported by two related observations: 1) no difference in initial reach trajectory or onset timing between the visual task conditions of when vision was available during the entire trial as compared to when vision was available prior to the onset perturbation only and 2) in the absence of visual information prior to the onset of perturbation there would be no difference in initial reach trajectory with respect to the differing handle locations (which would be characterized as a trajectory that was generic rather than target specific) but showing no difference in response latency. With regards to *where* in the visual field the visuospatial information regarding target location is available, we predicted that there would be no difference in initial reach trajectory between the visual task conditions of when vision was available during the entire trial and when vision was available prior to the onset perturbation only within a given target location. In other words, there would be no difference in initial reach trajectory for reaches performed under normal viewing conditions or reaches performed based on a stored visuospatial representation regardless of whether the target was mapped in the central or peripheral visual field.

3.2 Methods

3.2.1 Participants

Twelve healthy young adults (8 females, 4 males) participated in the study (aged 20 – 29, mean age = 23, SD = ± 2.52 years). All participants were self reported as being right handed, reported no neurological or musculoskeletal conditions that would affect their ability to recover balance and had normal or corrected to normal visual acuity. This study received clearance from

the Office of Research Ethics at the University of Waterloo and all participants provided written consent prior to study participation.

3.2.2 Protocol

Participants were seated in a custom built chair that delivered a whole body perturbation when it tilted backwards in the sagittal plane to a maximum angle of 20 degrees. The chair was held in the upright position with an electromagnet, and an elastic preload enhanced the initial acceleration of the chair when the electromagnet was released. A load cell was connected to the electromagnet so that perturbation onset could be determined in post processing. A handle with embedded force sensing resistors (FSR) was placed in one of three locations in the mediolateral plane with respect to a head centric reference frame of the participant: 1) directly anterior in the central field of view, 2) in a 20 degree visual periphery to the right and 3) in a 40 degree visual periphery to the right. Participants were asked to flex their right shoulder to 90 degrees and point to the position of the handle (0, 20 or 40 degrees with respect to a head centric reference frame). The handle was then translated forward so that it aligned with the participant's wrist while the chair was in the upright position. This was to ensure that handle locations were within reach of the participant (Figure 3.1). Peripheral target locations were in the right peripheral field of view as all participants were right handed and reaches were made with the right arm. The FSR was used to determine the time of hand contact with the handle.

A

Handle

0°

θ

100 msec post
Ant. Delt. Onset

90°

Ant. Delt. Onset

B
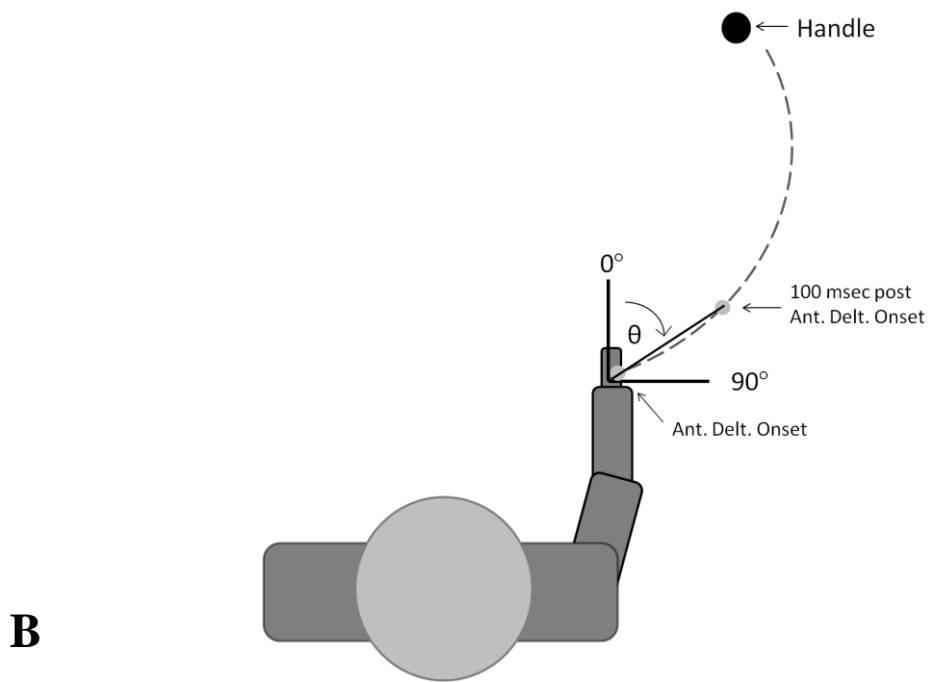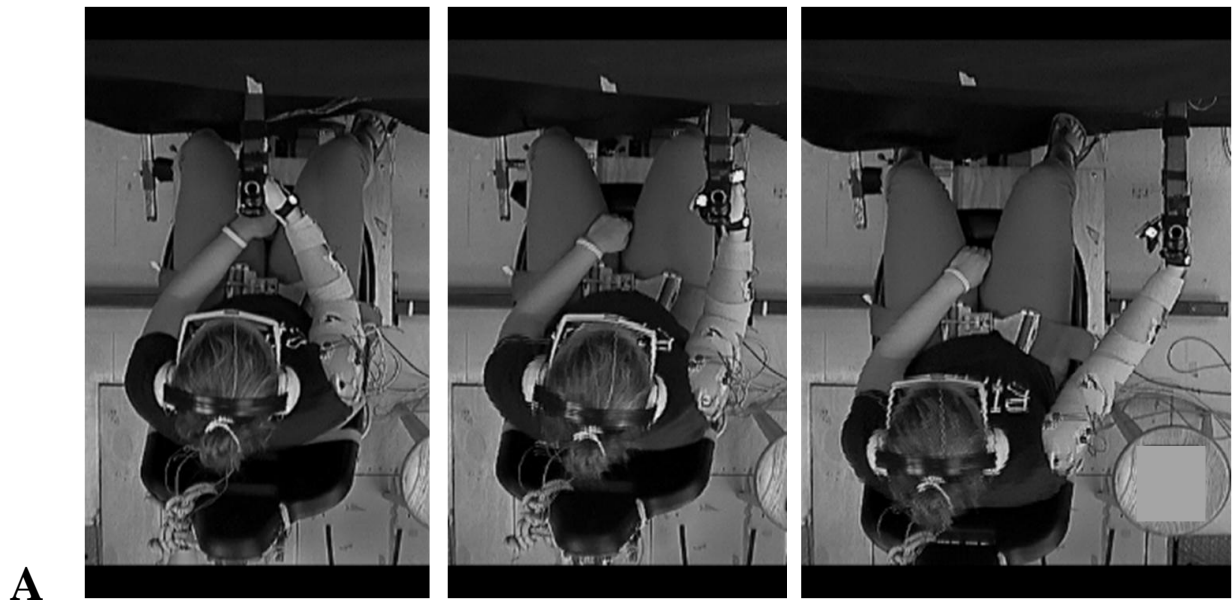
Figure 3.1: (A) Schematic of the overhead view of the participant and the alignment of the three handle locations; (B) Schematic for the calculation of the initial reach trajectory angle of the wrist.

Liquid crystal diode (LCD) goggles were worn throughout the experiment to control for the visual task conditions: 1) full vision (FV) - vision of the handle is available prior to, during and after perturbation, 2) map only (MAP) - vision is available prior to but not after perturbation onset and 3) online only (ON) - vision only becomes available after perturbation onset (Figure 3.2). A hard stop prevented the chair from tilting past approximately 20 degrees in the event that participants were unsuccessful at recapturing stability with the reach–to–grasp movement. Participants wore ear plugs and noise cancelling headphones to prevent responses being initiated from the sound of the magnet releasing.
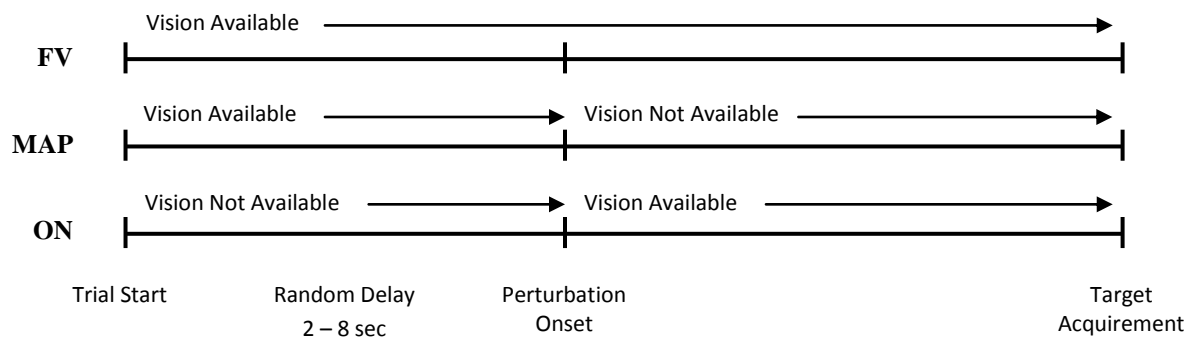
Figure 3.2: Schematic of the three visual task conditions full vision (FV), mapping only (MAP) and online only (ON) within the experimental paradigm.

While seated in the chair, participants received 90 perturbation trials fully randomized based on the three handle locations and three visual task conditions. Each trial was 12 seconds in duration and timing of perturbation onset was randomized between 2 and 8 seconds after the onset of the trial. Participants started each trial with their right arm resting comfortably on their right leg with the hand in an area marked out by tape on the anterior thigh that served as the start position for the hand. Participants were instructed to remain as relaxed as possible in between trials and to react as fast as possible in response to the perturbation by reaching with their right

arm to grasp the handle and regain stability. They were also instructed to keep their gaze fixed

directly in front of them to allow for the 20 & 40 degree handle locations to be presented in their

visual periphery; i.e. if the handle appeared to their right they were asked to refrain from fixating

on the target. A fixation point was provided for them to look at, and this fixation point was

placed in their central vision.

3.2.3 Instrumentation and Data Acquisition

Surface electromyography (EMG) was collected unilaterally from the following muscles

of the right arm: anterior deltoid, middle deltoid, biceps brachii, common wrist flexors and the

common wrist extensors. Common wrist flexors and extensor electrode placement was

approximately 3 cm distal to the elbow. Skin sites were first abraded with NuPrep skin

preparation gel and then cleaned with rubbing alcohol. Self–adhesive electrodes (Medi Trace,

Kendall 130) were placed over the muscle belly and oriented to the alignment of the muscle

fibers. A ground electrode was placed on the medial portion of the clavicle. EMG was collected

using a NorAxon system (Scottsdale, AZ, USA) and was filtered online from 10 to 300 Hz and

amplified at a set gain of 1000. The collection of EMG data was used to determine the latency of

the response to the perturbation as well as to examine the temporal order of muscle activation.

Electrooculography (EOG) was collected to confirm gaze behaviour instructions

(GRASS Technologies, West Warwick, RI, USA). Skin sites were abraded and cleaned in the

same manner as EMG. The electrodes were filled with a conductive gel and were placed on the

outer corner of each eye and above and below the left eye to monitor horizontal and vertical eye

movement respectively. A ground electrode was placed in between the eye brows.

Kinematic data were collected via Optotrak (Northern Digital Inc., Waterloo ON, Canada). A rigid body plate containing 4 infrared emitting diodes (IREDs) was placed on the posterior portion of the forearm approximately 3 to 4 cm proximal to the radial styloid process. IRED markers were placed at the acromioclavicular joint and on the headrest portion of the chair. A second rigid body plate containing 3 IREDs was attached to the superior portion of the support rail for the handle. Imaginary points were created at the elbow (lateral epicondyle) wrist (posterior forearm, midway between radial and ulnar styloid process), and top and bottom of the vertical handle using a digital probe. Initial reach trajectory was defined as the movement of the wrist with respect to the chair, within the first 100 msec from anterior deltoid onset. The coordinate system for trajectory is as follows: a positive value in the X direction represents anterior motion, positive values in the Y direction represents superior motion and positive values in the Z direction represents motion to the right. Initial reach trajectory of the wrist with respect to the chair in the ML plane within the first 100 msec of movement was calculated and used as the variable to quantify initial reach angle. Two time points (anterior deltoid onset and 100 msec post anterior deltoid onset) were used to calculate the initial angle of the reach trajectory. This value was then subtracted from 90 degrees so that the zero degree axis was the sagittal axis through the wrist. All analog data were collected digitized at a rate of 1200 Hz (Northern Digital Inc., Waterloo ON, Canada). All kinematic data were collected with the 6 channel strobers (NDI First Principles), sampled at 120 Hz. All data were collected via the Optotrak collection system (Northern Digital Inc., Waterloo ON, Canada) and were stored for offline analysis.

3.2.4 Data Analysis

Data were analyzed with a custom built LabView program (National Instruments, Austin TX, USA). EMG was bandpassed from 20 to 500 Hz with a 2nd order dual pass Butterworth

filter, notch filtered at 60 Hz, corrected for bias and full wave rectified. Muscle onset was

determined to be the point where the EMG signal remained 3 standard deviations above baseline

for 25 msec. The chair load was filtered through a dual pass 4th order Butterworth filter with a

low frequency cut off of 75 Hz. Perturbation onset was defined as the point where the chair load

fell beneath 3 standard deviations of a resting baseline. FSR was filtered through a dual pass 4th

order Butterworth filter with a low frequency cut off of 50 Hz. Hand contact time was used to

define the end of the response, and was determined to be the point where the signal was at 0.3

volts. EOG signals were band pass filtered from 0.1 to 35 Hz with a 2nd order dual pass

Butterworth filter.

Trials that showed saccadic eye movements prior to or during perturbation were

documented to determine the ability to execute the compensatory reaches in the absence of gaze

shifts. These trials, based on the low frequency (2.5% of all trials), were discarded from later

analysis. In addition, trials characterized by preparatory EMG activity in anticipation of a

perturbation were also discarded (5.2% of all trials).

3.2.5 Statistical Analysis

Task comparisons were conducted using a two-way repeated measures ANOVA (factor

1: handle position (3 levels) and factor 2: visual condition (3 levels)).   A one–way ANOVA was

used to compare the initial reach angle of the ON visual condition within the three handle

locations. Post hoc analysis was performed using Tukey's test with a significance value of p =

0.05. Values were averaged within task conditions within participants and statistical analysis was

run on the resultant means.

3.3 Results

3.3.1 Initial reach trajectory

Despite the rapid responses of the upper limb, reach response characteristics were not generic when visuospatial information was available prior to perturbation onset. Initial reach trajectory approached a main effect for vision ($F_{(2,22)} = 3.21$, $p = 0.06$) and had a main effect of handle location ($F_{(2,22)} = 32.61$, $p < 0.001$). There was a statistically significant interaction effect for vision and handle location ($F_{(4,44)} = 12.40$, $p < 0.001$) . Post hoc testing revealed that there was a significant difference in initial reach angle for the FV condition between the 0 & 20 degree ($p = 0.003$) and 0 & 40 degree ($p < 0.001$) but not the 20 & 40 degree ($p = 0.7858$) handle locations. Post hoc testing revealed that there was a significant difference in initial reach angle for the MAP condition between all target locations [0 & 20 degree ($p < 0.001$), 0 & 40 degree ($p < 0.001$), and 20 & 40 degree ($p = 0.021$)] (Figure 3.3). Post hoc testing comparing initial reach angle between FV and MAP revealed no differences in initial reach angle for the handle locations of 0 degrees ($p = 0.91$) and 20 degrees ($p = 0.76$) such that average initial wrist trajectories for the 0 degree target location were $31.76° \pm 14.1°$ and $27.6° \pm 12.33°$ for FV and MAP respectively while average initial wrist trajectories for the 20 degree target location were $47.09° \pm 16.55°$ and $52.24° \pm 13.00°$ for FV and MAP respectively. However, there was a difference in initial reach angle for the 40 degree handle location between the visual conditions of FV and MAP ($p = 0.019$) such that mean initial wrist trajectory was $52.09° \pm 15.34°$ and $63.28° \pm 14.38°$ for FV and MAP respectively (Figure 3.4).
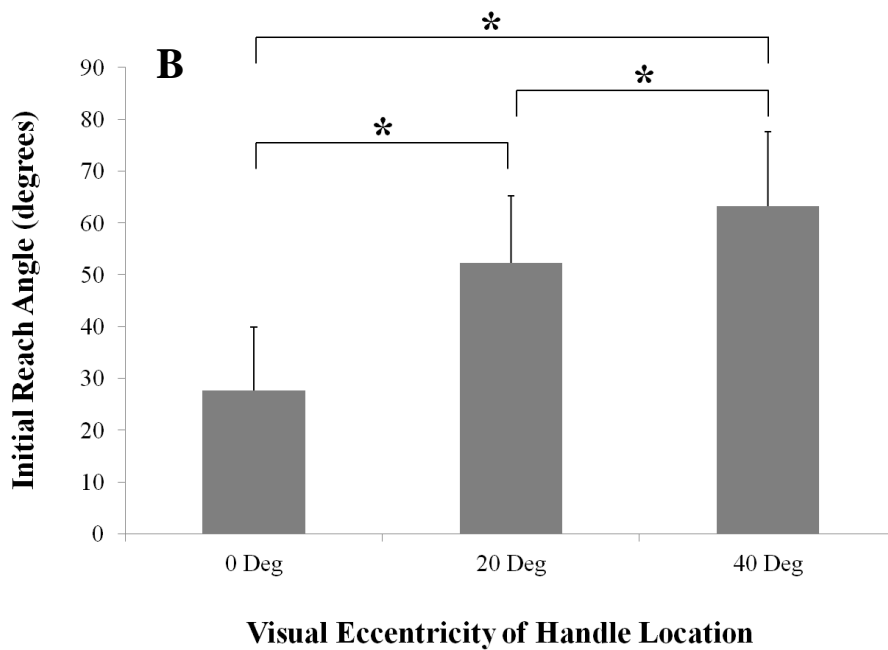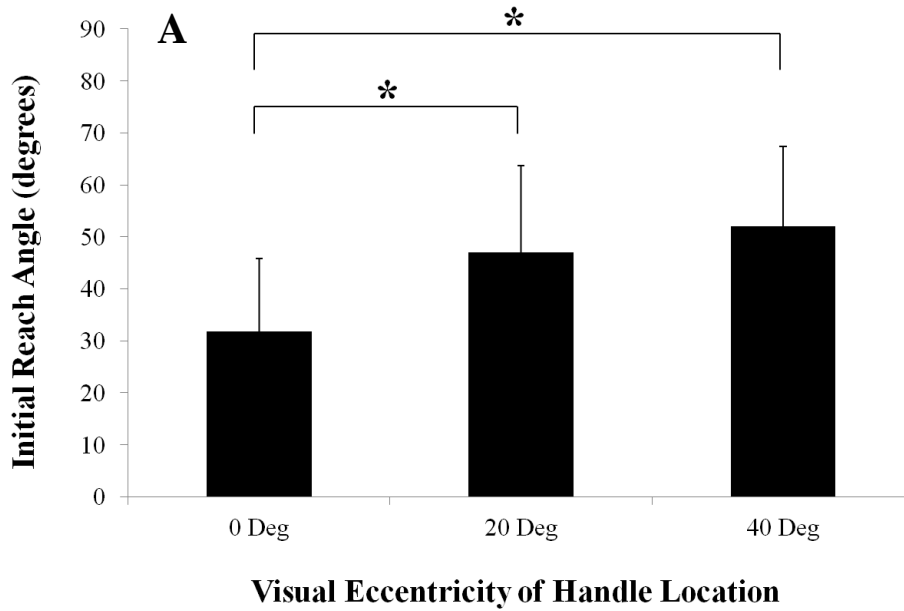
Figure 3.3: Interaction effect for visual task condition and handle location within a specific visual task condition: (A) Average initial reach angle (and standard deviation) for the full vision (FV) condition; (B) Average initial reach angle (and standard deviation) for the mapping only (MAP) condition; * denotes statistically significant differences ($p<0.05$).
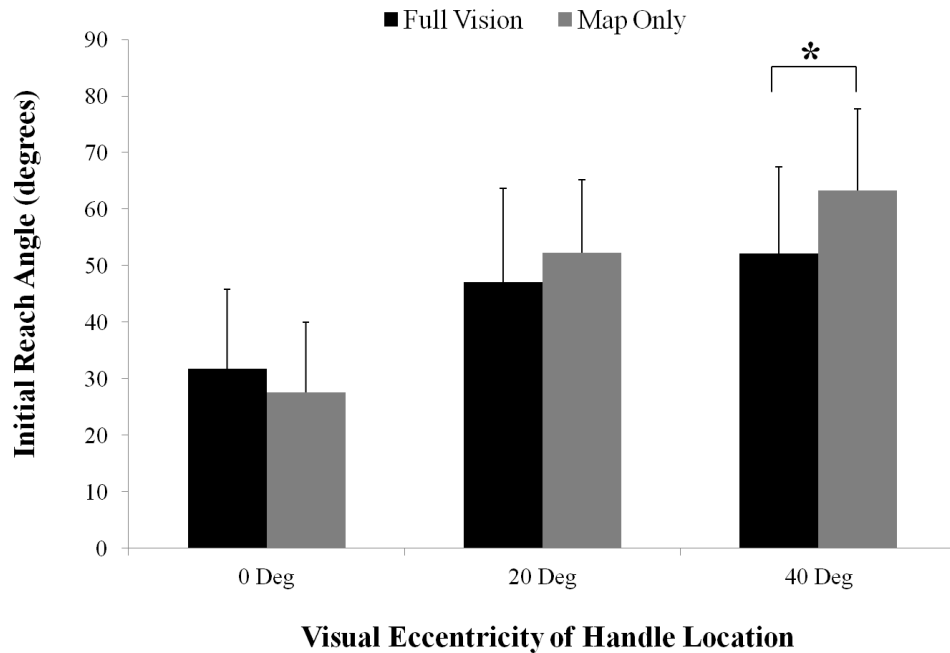
Figure 3.4: Interaction effect examining differences in the average (± SD) initial reach angle for each of the handle locations comparing between the visual task conditions of full vision (FV) and mapping only (MAP);* denotes statistically significant differences (p<0.05).

A one way ANOVA examining initial reach angle in the ON visual task condition revealed a trend towards s significant difference in initial reach angle between the handle locations ($F_{(1,22)} = 3.02$, $p = 0.07$) such that the mean initial reach angles in the ON condition were 38.66° ± 11.77° , 38.88° ± 14.31° and 46.73° ± 17.01° for the 0, 20 and 40 degree handle locations respectively (Figure 3.5).
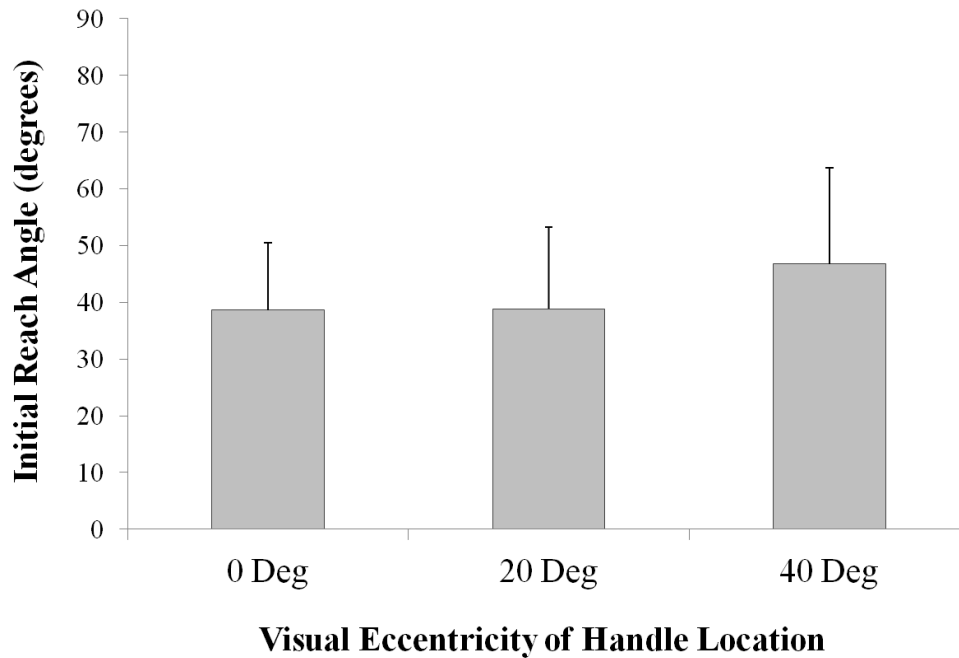
Figure 3.5: Average initial reach angle (and standard deviation), with respect to the AP location of the wrist for the online (ON) condition. There was a trend towards a statistically significant difference in initial reach trajectory between the 0°, 20° and 40° handle locations (p=0.07).

3.3.2 Reaction times

All EMG onsets had a main effect of visual condition, such that onsets were faster in the MAP condition when compared to both the FV and ON conditions, while there were no differences between the FV and ON conditions. Anterior deltoid onset latency was significantly different comparing across visual conditions $(F_{(2,22)} = 12.88$, $p < 0.001)$ and handle locations $(F_{(2,22)} = 15.19$, $p < 0.001)$ but did not show an interaction effect $(F_{(4,44)} = 0.65$, $p = 0.63)$. Post hoc testing revealed that a significant difference between FV and MAP as well as MAP and ON $(p < 0.001$ and $p = 0.001$ respectively). There was a trend towards a significant difference in EMG onset between FV and ON $(p = 0.055)$. The mean anterior deltoid onsets for the visual conditions of FV, MAP and ON were 111, 99 and 106 msec respectively. Middle deltoid onset

latency showed a main effect of vision ($F_{(2,22)} = 15.52$, $p < 0.001$) but was not different between handle locations ($F_{(2,22)} = 0.84$, $p = 0.44$) and there was no interaction effect ($F_{(4,44)} = 0.81$, $p = 0.52$). Post hoc testing revealed a significant difference between FV and MAP as well as MAP and ON ($p < 0.001$ and $p = 0.0013$) respectively. The mean middle deltoid onsets for the visual conditions of FV, MAP and ON were 106, 93 and 102 msec respectively. Biceps onset latency also was significantly different between visual conditions (($F_{(2,22)} = 15.93$, $p < 0.001$) and handle location ($F_{(2,22)} = 13.77$, $p < 0.001$) but did not show an interaction effect ($F_{(4,44)} = 0.49$, $p = 0.75$). Post hoc testing revealed statistically significant differences between FV and MAP as well as MAP and ON ($p < 0.001$ and $p = 0.0014$) respectively. The mean bicep onsets for the visual conditions of FV, MAP and ON were 110, 96 and 106 msec respectively. Post hoc testing revealed significant differences between the 0 and 20 degree handle locations as well as the difference between the 0 and 40 degree handle locations ($p = 0.003$ and $p < 0.001$) respectively. The mean bicep onset latency for the handle locations of 0, 20 and 40 degrees were 98, 106 and 108 msec respectively.

Wrist flexors onset latency was different across vision conditions ($F_{(2,22)} = 10.21$, $p < 0.001$) but did not show a main effect of handle location ($F_{(2,22)} = 28.34$, $p < 0.001$) nor an interaction effect ($F_{(4,44)} = 0.80$, $p = 0.53$). Post hoc testing revealed a significant difference between FV and MAP as well as MAP and ON ($p < 0.001$ and $p = 0.016$) respectively. The mean wrist flexor onsets for the visual conditions of FV, MAP and ON were 214, 197 and 208 msec respectively. Wrist extensors onset latency showed a main effect of vision ($F_{(2,22)} = 17.86$, $p < 0.001$) but did not show a main effect of handle ($F_{(2,22)} = 0.92$, $p = 0.41$) nor an interaction effect ($F_{(4,44)} = 1.39$, $p = 0.25$). Post hoc testing revealed that there was a significant difference in EMG onset between FV and ON ($p = 0.0431$), between FV and MAP ($p < 0.001$) and between

MAP and ON ($p = 0.0074$). The mean wrist extensor onsets for the visual conditions of FV, MAP and ON were 111, 91 and 102 msec respectively.

3.3.3 Response times

Response time showed a main effect of vision ($F_{(2,22)} = 10.04$, $p < 0.001$) and a main effect of handle ($F_{(2,22)} = 9.17$, $p = 0.001$) but no interaction effect ($F_{(4,44)} = 1.77$, $p = 0.15$). Post hoc testing revealed that participants had faster mean ($\pm$ SD) response times in the MAP condition (355 ± 45 msec) when compared to both the FV condition (370 ± 42 msec, $p = 0.046$) and also when compared to the ON condition (381 ± 47 msec, $p = 0.005$). Participants had a longer mean response time for the handle located in the 40 degree peripheral visual field (387 ± 43 msec) when compared to both the 20 degree handle location (364 ± 41 msec, $p = 0.0184$) and the 0 degree handle location (355 ± 50 msec, $p = 0.0012$).

3.3.4 Movement velocity

Mean peak wrist velocity was 2.77 ± 0.27 m/s and did not show a main effect of vision ($F_{(2,22)} = 3.13$, $p = 0.064$) nor a main effect of handle location ($F_{(2,22)} = 1.38$, $p = 0.27$). Peak wrist velocity as a percentage of movement time did not show a main effect of vision ($F_{(2,22)} = 0.55$, $p = 0.58$) , nor a main effect of handle location ($F_{(2,22)} = 1.29$, $p = 0.30$). The mean timing of peak wrist velocity as a percentage of movement time was $69.8 \pm 5.1\%$.

3.5 Discussion

The present results support the hypothesis that the initial phase of a compensatory reach–to–grasp reaction can be guided by visuospatial information acquired prior to onset of perturbation. This was revealed by target specific differences in initial reach trajectory when

visual information was only available up to the time of perturbation onset. Additional support for this hypothesis came from the observation that when visual information was only available after the onset of perturbation, participants did generate a generic initial reach angle (i.e. the initial reach was not target specific). Our results partially support our hypothesis regarding where in the visual field the visuospatial information originates from. Specifically there were no differences in initial wrist trajectory in the 0 and 20 degree handle locations. However, this did not hold true for the 40 degree handle location. Differences did appear between the visual task conditions of full vision and map only for this more peripheral handle location. Overall, in the map only condition participants adopted a wider initial reach angle with respect to the AP direction of the wrist. This leads to the view that while peripheral visual information can be used individuals may adopt different strategies for environmental interaction based on said maps as the eccentricity of the visual information increases in order to ensure a successful reach–to–grasp movement.

3.4.1 Influence of WHEN visual information is acquired

Numerous studies have examined the role of vision in volitional reach–to–grasp / reach–to–point paradigms. The literature supports the finding that individuals are able to perform these movements successfully when online visual feedback is available and when reaching to a remembered target location, suggesting that it is likely that both stored and online visual feedback are important in this process (Ricker et al., 1999). However, when these movements are performed under conditions with no visual feedback, participants adopt compensatory strategies to ensure successful target acquisition, including reducing the speed of their movement and increasing grip aperture during the terminal contact phase of the reach (Ricker et al., 1999).

So how do we adapt when we are required to move quickly? In compensatory reach–to–grasp investigations, participants appear to have no difficulty in successfully executing a response that is able to arrest the induced whole body motion when complete removal of the visual scene occurs with perturbation onset or when the target is located in the peripheral visual field (Ghafouri et al., 2004; King et al., 2010, 2011). Out of necessity, compensatory balance responses have EMG reaction times that are approximately twice as fast as those of rapidly initiated volitional movement (Gage et al., 2007). Likewise, overall response times are much quicker in compensatory reactions, yet interestingly, the same temporal characteristics of reaching kinematics, such as the percentage of movement time at which peak velocity occurs and at which maximum grip aperture occurs, are preserved in these temporally urgent reactions (Gage et al., 2007; Lakhani et al., 2011). It is noteworthy to point out that in spite of the control challenges placed on the CNS, muscle reaction times did not vary based on task conditions and were consistent with the expected ~ 100 msec latency and response times ranged from 355 – 387 msec depending target location (targets further in the eccentricity of the visual field had a longer response times). Similar to the strategies adopted in volitional reaching studies where no visual feedback is available during the movement, participants adopted a similar strategy in this experiment. For the 40 degree target in the mapping condition, participants had a tendency to initially overshoot the target and reach back to grab it with a swiping motion. Again, this may be a strategy adopted to aid in ensuring successful re–stabilization. Strategically it is beneficial to initially overshoot the target location and initiate rapid shoulder, elbow or wrist movements to re – orient the hand in order to grasp the handle while falling away from it than it is to initially undershoot the target and need to continue forwards with the entire upper limb and torso.

Interestingly, participants were able to successfully grasp the handle when no visuospatial information regarding target location was available prior to perturbation and only after the onset of perturbation. While participants had a tendency towards a generic initial reach response, they were able to make corrections to reach trajectory with online visuospatial information in order to successfully grasp the handle to regain stability. This is especially interesting as response times for the online only condition were an average of ~380 msec and were not statistically different from the full vision condition which had an average response time of ~ 370 msec. The minimal latency for incorporating visual information into a motor program is approximately 200 msec (Paillard, 1996); any changes to the reach trajectory required to successfully grasp the target would have had to occur very rapidly due to the rapid nature of the response. Conversely, it may be possible that we have the ability to increase the speed at which we process online visual information and the speed at which it can be incorporated into the ongoing motor program in circumstances when there is a threat to whole body stability. Lakhani et al. (2011) demonstrated that individuals respond to whole body instability at latencies characteristic of those initiated in response to perturbation forces regardless of whether or not the movement resulted in the ability to re–stabilize the COM. This may speak to potential differences in how the CNS interprets and integrates incoming sensory information in order to produce rapid latency responses. Therefore, while pre–perturbation visuospatial information may be of importance for the initial phase of a compensatory reach to grasp reaction, we cannot rule out the contribution of online visual control to the later portions of the reaction and / or re–stabilization phase despite the temporal urgency of these reactions. We also cannot rule out the possibility of some pre–planning of initial reach trajectory in the online only visual task condition as there were a limited number of target options available to the participant.

3.4.2 Influence of WHERE visual information is acquired

Reach to grasp movements are more accurate when the hand and the target are located within the central visual field (Clavagnier et al., 2007; Prado et al., 2005). However, in natural reaching movement sequences, the hand starts in the peripheral visual field and moves into the central visual field as it gets closer to the target (Bedard & Proteau, 2004). Manual reaching and aiming movements can be made solely in the peripheral field of view, however these movements do tend to be less accurate due to the low spatial resolution associated with the peripheral retina (Clavagnier et al., 2007; Prado et al., 2005). The current work revealed that as objects are presented at increasing visual eccentricity, there is an impact to the strategy that becomes associated with the compensatory reach–to–grasp movement. King et al., (2010) examined compensatory reach–to–grasp responses in a paradigm where final target location prior to perturbation was unpredictable due to the use of a motorized handhold. Final target locations were 20, 30 or 40 degrees of visual eccentricity, and the authors concluded that while participants were successful at re–stabilization, there was greater deviation from a straight line reach trajectory for the furthest target location (King et al., 2010). These results are similar to ours in that when subjects were required to rely on a visuospatial map of the 40 degree target, they initially reached wide of the target. We actively visually scan our environment for relevant features needed to guide a movement within that environment (Franchak & Adolph, 2010). Under volitional movement conditions there is a high demand of accuracy in the visuospatial representation of the target or target area so as to allow for correct interaction with such an object (Franchak & Adolph, 2010). Arguably, this demand is greater in the case of an unexpected perturbation, where failure to engage in the correct limb response / surface contact has the potential to result in a fall or an injury. One might argue that a prior planning of reach

trajectories is done as a way of preparing for the possibility of instability, as compensatory responses to whole body instability cannot be planned for due to the unpredictable nature of when one will experience a perturbation and its associated parameters. While in this experiment, the target handle was located in the visual periphery, we cannot rule out the possibility that in real life situations, visual scanning of the surrounding environment allows us to foveate temporarily on various aspects of the environment, which may potentially enable us to extract relevant features of objects, such as size, orientation, colour, and potential stabilizing properties (King et al., 2011). As a result of this knowledge gained prior to a perturbation, those properties may be incorporated along with the online visuospatial location of a hand hold target located in the visual periphery. Alternatively, minute features of potential reach–to–grasp targets gained from central vision may not be of the same "importance" level as the actual location of the target, which appears to be able to be acquired from the peripheral field of view.

Visual impairments that limit the field of view available to the individual as well as the quality of the visual information are risk factors associated with falls, particularly in older adults (Lord, 2006). Individuals with cataracts have limited peripheral visual information available to them and thus may not be able to create or use precursory maps created from the visual periphery. This has the potential to increase fall risk by introducing reaction delays associated with head and neck rotation and / or saccade initiation towards a target in order to capture the target area within the central visual field (King et al., 2011). Conversely, individuals with macular degeneration may be forced to rely solely on peripheral visual information which may increase visuospatial processing time requirements due to low spatial acuity (Tovee, 1996).

3.4.3 Mechanisms of spatial mapping for use in reaching

If pre–perturbation visuospatial information can be incorporated into compensatory reactions, then how do we create these intrinsic maps of our external environment? One suggested mechanism is the use of a retinotopic map. This theory suggests that we maintain a copy of current retinal information in a retinotopic coordinate framework, and this map is updated on a saccade to saccade basis (Prado et al., 2005; Wandell et al., 2007; Wurtz, 2008). However, our participants were instructed to refrain from making saccades and to continually fixate on a central fixation point. Intracellular recordings of non-human primates revealed that not only were neurons in the current visual receptive field active, but neurons in remote areas that would become the future receptive field after a saccade was made were also active, *prior* to saccade initiation (Colby et al., 1995; Duhamel et al., 1992). Therefore, it may be possible that while even though subjects were fixating their gaze straight ahead they were suppressing saccades to the actual target location. The neurons in this new receptive field of where they wished to shift their gaze towards may have been facilitating their ability to map peripherally located targets (Duhamel et al, 1992; Wurtz, 2008).

Another hypothesis is that the retinotopic coordinates of exteroceptive information are transformed into a spatiotopic map, such that visual perception is no longer in the coordinate system of the eyes, but rather in the coordinates of actual egocentric visual space (Wurtz, 2008). Individuals may create such reference frames in a parallel manner or may switch between the two coding systems and use of the two types of reference frames as necessary depending on the task. The coding of target location in a retinotopic representation may also follow the ventral visual stream hypothesis, enabling individuals to discern the "what" characteristics of the environmental surround, whereas the spatiotopic representation may follow the dorsal visual

stream, as similar cortical areas (posterior parietal cortex, lateral intraparietal sulcus and parieto–occipital junction) are involved in identifying "where" an object is in space (Prado et al., 2005). This may have an implication on the need for scanning and updating of visuospatial representations. Retinotopic maps are constructed based on the continuous movement of the eyes, and therefore may be required to be updated on a moment to moment basis (Wurtz, 2008). However, spatiotopic representations based on egocentric and allocentric reference frames may be more stable depending on the static vs. dynamic nature of the individuals' current environment, and thus may not be required to be updated as frequently.

3.4.4 Speed of compensatory reactions

There were no significant delays in EMG latency regardless of the visual task condition or the handle location reinforcing the notion that individuals prioritize the attempt of maintaining postural stability irrespective of the demands imposed by the experimental condition. In other words, we do not slow our response to perturbation forces so as to first survey the scene and incorporate relevant exteroceptive information into our response. Instead, as our results demonstrate from the online only visual task conditions, we initiate an appropriate response and then make corrections as necessary once the response is underway. One suggestion for the rapid initiation speed is that, in addition to the need to arrest body motion, early activation of the muscles may allow for more adjustments to be made to the chosen response, such as multiple steps or the addition of an upper limb response after first initiating a lower limb response (Maki et al., 2003).

3.4.5 Limitations

Post processing analysis found that the mean timing of the closing of the shutters in the MAP condition was approximately 100 msec prior to perturbation onset, while the opening of the shutters in the ON condition was 100 msec prior to perturbation onset. A benefit to this timing difference is that it allows for the decay of retinal afterimage on the inside of the LCD goggles prior to perturbation onset in the MAP condition and also allows for light accommodation prior to perturbation onset in the ON condition. One might speculate that the early closing of the shutters in the MAP condition acted as the cue to respond, as seen by the statistically faster EMG onsets in the MAP condition (mean differences between EMG onsets when comparing the MAP condition to both the FV & ON conditions were ~10 msec for all of muscle groups). If the shutters were serving as the cue to respond, we would expect to see statistically faster muscle activation in the ON condition as well when compared to the FV condition, and this was not observed. It may be possible that the shutters were acting as a cue to respond, and that the statistically faster response in the MAP condition but not in the ON condition may potentially be linked to a sense of fretfulness of having vision removed just prior to perturbation as opposed to having vision restored momentarily before perturbation.

Another potential limitation is that while the visual task condition and the handle location were randomized between every trial, subjects were reaching towards a stationary object with limited spatial locations in a predictable manner (i.e. the chair always perturbed in the same direction and at the same rate). Instructions provided to the participant may have inadvertently prompted them to remember the location of the target and calculate reach vectors towards the target prior to perturbation onset in the full vision and mapping conditions when vision was available prior to the release of the chair. The static nature of the participant prior to perturbation

onset, the limited number of handle locations (all within the same horizontal meridian and all within the right half of peri–personal space) and the absence of environmental distracters may have also contributed to the ease with which participants were able to store a visual representation and thus their ability to more successfully rely on the stored internal representation when initiating compensatory reach–to–grasp reactions.

3.5 Conclusions

The results of this study provide support for the ability to create precursory visuospatial maps with peripheral visual information and use this information to guide compensatory reach–to–grasp reactions. Participants adopt more conservative reach strategies at increasing visual eccentricities when reliant on stored representations, but are able to successfully recapture stability and initiate the response at latencies of ~ 100 msec regardless of visual task condition or handle location. Future research may aim to examine the "accuracy" of visuospatial maps when tight spatial constraints are imposed on the participant. If more precise terminal reach accuracy is required, mapping may become even more important out of necessity. This may be reflected by less variation in the initial reach angle(s), or conversely, no changes to the initial phases of the reach but differences arising upon target contact. Another potential area of focus are the temporal features associated with the creation and storage of an intrinsic visuospatial map, including the minimal visual sampling time of the environmental surround that would be required in order to create a map adequate enough to act upon, as well as the temporal features associated with how often these maps require updating.

Chapter 4: Study 2

The influence of dual task interference on mapping peripherally located targets during reach–to–point movements

4.1 Introduction

Balance reactions are temporally urgent reactions that occur at rapid latencies. These reactions aim to recapture the center of mass (COM) within the base of support (BOS) of the body in order to arrest whole body motion induced by a perturbation (Bouisset & Do, 2008; Maki & McIlroy, 2006; Maki et al., 2003). These reactions have been demonstrated to occur at latencies of 80 to 100 msec; approximately twice as fast as rapidly initiated volitional movements (Ghafouri et al., 2004; McIlroy & Maki, 1995). Traditionally these temporally urgent reactions have been considered to be automated processes initiated by sub–cortical structures (McIlroy & Maki, 1995; Zettel et al., 2008). However studies examining postural stability in conjunction with the performance of a concurrent cognitive task have demonstrated the influence of higher cortical structures in the maintenance of balance (Jacobs & Horak, 2007; Maki & McIlroy, 2007). In particular, visual attention may be especially important for the incorporation of exteroceptive information in order to guide limb trajectory (stepping and / or reaching) within environmental constraints (Maki et al., 2003; Zettel et al., 2008).

While visual, vestibular and somatosensory afference contribute to balance control, vision arguably has an integral role in postural maintenance. Vision provides us with a reference frame with respect to the external environment and provides us with information regarding specific environmental features such as obstacles, support surface properties and changes in surface elevation (ramps, stairs, etc.) (Scovil et al., 2008). Vision also provides feedback with respect to the body itself: limb position and orientation as well as distance vectors with respect to

44

where our limb is currently positioned with reference to obstacles and support surfaces (Maki &

McIlroy, 2005; Paillard, 1996). Therefore, it is imperative that visual information regarding the

environmental surround be incorporated into temporally urgent balance reactions so as to

properly guide limb movement for effective re–stabilization.

The extent to which online visual feedback can be incorporated into balance reactions

may be limited. Delays associated with head movements or visual saccades in order to foveate on

support surface locations would serve to increase response times with respect to the onset of a

perturbation (King et al., 2011). Therefore, it may be necessary to acquire visuospatial

information regarding the environmental surround on an ongoing basis and store transient

representations of the environment to act upon in the event of a perturbation (Ghafouri et al.,

2004; Scovil et al., 2008).

Compensatory reach to grasp reactions can be coordinated by relying on visuospatial

information acquired prior to the onset of perturbation. Initial wrist trajectories have been shown

to be specific to the location of handhold targets as opposed to being directly affected by the

visual task conditions of having normal vision throughout a reach as compared to having visual

feedback removed at the onset of perturbation (Ghafouri et al., 2004; Williams et al.,

unpublished data). Similar results have also been demonstrated with compensatory stepping.

Zettel et al. (2005) examined performance of perturbation evoked stepping in conjunction with

the performance of a concurrent visuomotor tracking task performed with the upper limb under

various environmental constraints. The study was designed so that an obstacle and a targeted

landing site were only visible in the lower visual field (Zettel et al., 2005). Interestingly,

participants rarely required downward gaze shifts during the trial in order to successfully meet

the task demands of the environmental constraints (Zettel et al., 2005). These studies support the

ability to acquire visuospatial information prior to perturbation onset, as well as the ability to transiently store that information in memory and use that representation to carry out perturbation induced stepping and reaching responses.

A second important element is whether the visuospatial information is being acquired from the central or peripheral visual field. The temporal urgency associated with balance restoration imposes tight constraints on the time available post perturbation to process incoming visual information. Delays associated with saccade latencies and head & neck rotational movements coupled with the delays associated with online acquisition of visual information led us to speculate that visuospatial mapping from the peripheral visual field may have a very prominent / beneficial role in pre–perturbation mapping. The importance of peripheral vision is linked to the unpredictability of natural moments of instability, specifically with respect to timing, direction and amplitude of perturbations. Naturally occurring perturbations may require a reaction to a range of possible options / spatial locations. King et al., (2010) specifically examined the contribution of peripheral vision in perturbation evoked reach–to–grasp reactions. The authors found that participants were able to recapture stability when the visual eccentricity of a handhold was as great as 40 degrees. Further exploration of the incorporation of peripheral vision into balance reactions found that initial reach angles did not differ between conditions of normal, unrestricted vision and reaches made when vision was only available prior to perturbation onset, when the handhold was located within a 20 degree visual eccentricity of central vision (Williams et al., unpublished data). For a target located at 40 degrees of visual eccentricity, participants were able to successfully regain stability when vision was removed at perturbation onset; however, they adopted a more conservative reach strategy such that they

would overshoot the target and reach back to grab it with a swiping motion (Williams et al., unpublished data).

Given the importance of the peripheral visual field and the reliance on mapping, there is a need to better understand the factors that may influence the capacity or effectiveness of such visuospstial mapping. Of specific interest is the potential role of concurrent attention demanding tasks on the ability to effectively map from the peripheral field of view. This has important implications to the control of visuospatial mapping in natural settings where individuals may be currently involved / partaking in an attention demanding task when they experience a loss of stability. Previous research has demonstrated that attention demanding tasks located within the central visual field limit the ability of individuals to attend to objects located further in the peripheral visual field. This is referred to as a narrowing of the functional field of view (FFOV). The functional field of view is defined as the maximum distance a stimulus can be displaced from the area of visual fixation and still be reliably detected without any head, neck or saccadic eye movement (Ball et al., 1988; Scalf et al., 2007). It has been established in the literature that the FFOV decreases when the eyes remain fixated on point of interest, and that it decreases further still once a secondary task requiring the utilization of cognitive resources is additionally implemented (Ball et al., 1988, 1993). While young, healthy individuals have little difficulty extracting relevant environmental features from the peripheral field of view in the presence of visual distracters this process becomes increasingly difficult for older individuals (Ball et al., 1988, 1993; Scalf et al., 2007). Therefore, it may make the localization of stabilizing objects, such as railings, more difficult to detect when they are located in the visual periphery.

The objective of this study was to examine the potential influence of attention on mapping peripherally located targets. While future studies will focus on perturbation and balance

47

reactions, the current study is focused on a voluntary visuomotor reaching paradigm. A volitional paradigm was used to test this hypothesis to prevent additional confounding factors associated with balance perturbation paradigms, such as increased arousal levels and increased severity of consequence if the resultant motor output is unsuccessful at regaining stability. We implemented a reach–to–point paradigm to examine the potential effects of a secondary visual attention task on the ability to encode target location prior to movement initiation. Presumably, the addition of a secondary visual attention task would impede our ability to encode a spatially accurate map of peripherally located targets, resulting in a less detailed or inaccurate visuospatial map. The decreased accuracy of this map would in turn lead to errors in motor performance such that the amplitude of spatial error in the reach–to–point paradigm would increase.

It was hypothesized that absolute horizontal pointing error, measured as the horizontal distance from the center of the target, would increase as a function of: A) visual task condition, such that errors would be greater when the reach–to–point was performed with no visual feedback as compared to continuous visual feedback, B) central task condition, such that errors would be greater when participants were required to peripherally map the target location while performing a secondary visual attention task as compared to a simple fixation task, and C) visual eccentricity of target location, such that pointing error will increase with increasing visual eccentricity of the target.

4.2 Methods

4.2.1 Participants

Eleven healthy young adults (4 females, 7 males) participated in the study (aged, mean age = 26.3, SD = 5.2 years). Participants were right handed and reported no neurological or musculoskeletal conditions that would affect their ability to recover balance and had normal or

corrected to normal visual acuity. This study received clearance from the Office of Research

Ethics at the University of Waterloo and all participants provided written consent prior to study

participation.

4.2.2 Protocol

Participants performed 120 reach–to–point movements broken down into 4 blocks of 30

trials. The three task manipulations were: 1) visual task condition [full vision (FV) or mapping

(MAP)], 2) central task condition [no concurrent task (SINGLE) or concurrent colour

discrimination task (DUAL)] and 3) visual eccentricity of target location. The four trial blocks

consisted of 1) full vision with single task performance, 2) mapping with single task

performance, 3) full vision with dual task performance and 4) mapping with dual task

performance. Within each block, the location of the reach–to–point target was randomized

between one of three locations: 15, 30 or 40 degrees to the right.

Participants were seated in a sound proof booth in front of a touch screen monitor. The

monitor was positioned 42 cm anterior to the participant's sternum. A wireless keyboard was

placed on the desk with the middle of the space bar positioned 10 cm to the right of the

participant's midline, as well as 10 cm inwards from the edge of the table. Participants were

instructed to use their right index finger to depress the space bar, and release it to execute the

reach–to–point movement when cued to do so. A 1 x 1 cm piece of felt material was attached to

the center of the space bar so that participants brought their hand back to the same start position

on the space bar for each trial (Figure 4.1). Participants were instructed to sit comfortably with

their chin in a chin rest to prevent head movement. The chin rest was positioned directly in front

of the midline of the participant, and affixed to the table that housed the monitor and the

keyboard. The height was adjusted so that participants were able to sit in an erect position

without the potential for neck discomfort. Liquid crystal diode (LCD) goggles were worn throughout the experiment to control when visual information was available based on the visual task conditions of: 1) full vision (FV) - vision was available prior to and during the reach execution, and 2) map only (MAP) - vision was available prior to but not after reach initiation. Noise cancelling headphones equipped with speakers were also worn to deliver a tone to participants. This tone was the cue to reach to point to the target.

As noted there were two central cognitive task conditions: 1) a fixation point (SINGLE) and 2) a dual task paradigm (DUAL). In the SINGLE condition, the letter "X" was presented on the screen and participants were instructed to keep their gaze fixated on the "X" and not to redirect their gaze to the target when it appeared in the periphery. In the DUAL condition a colour discrimination task was used to increase the attentional demands required by the participant within the central visual field. In this paradigm, two square boxes 1.22 x 1.63 cm were placed side by side in the same location as the "X" in the SINGLE condition. The hue of the colour of both boxes ranged from black to light blue and changed every 750 msec until the participant was presented with the tone. In the DUAL trials, participants were instructed to rest their left index finger on the "S" key and were asked to depress the "S" key whenever they perceived the hues of the two colour boxes to be the same. Otherwise, they were not to respond. The central cognitive task was removed from the screen at the same time as the sound of the tone, cuing the reach–to–point movement.
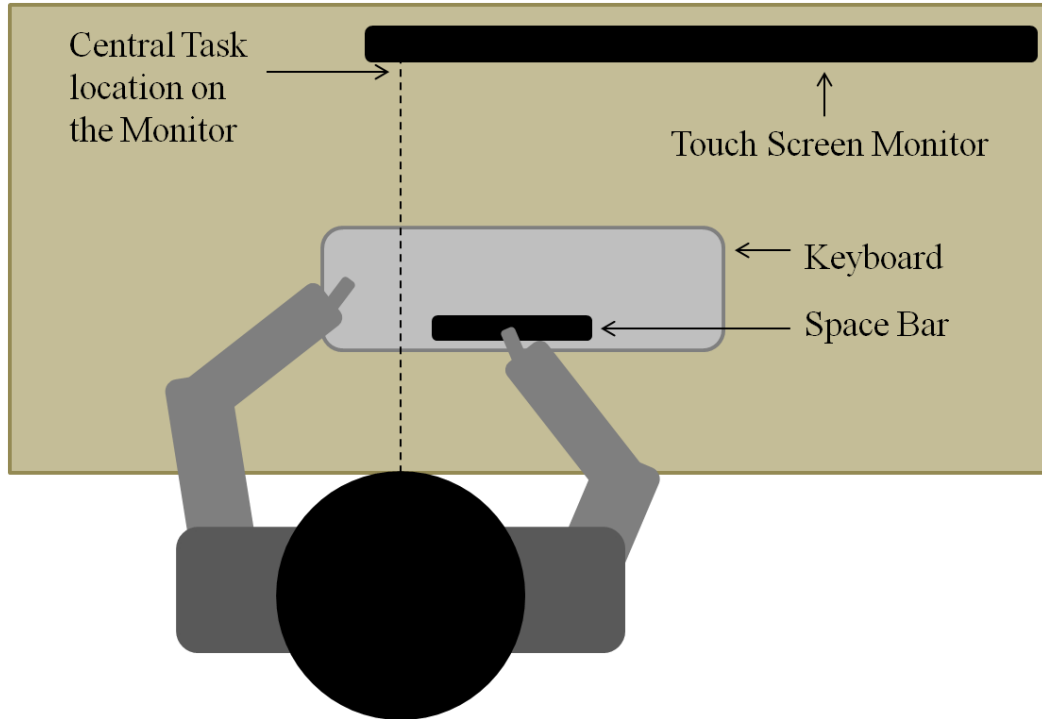
Figure 4.1: An aerial view of the participant set up at the touch screen computer. The right index finger was placed on the space bar and in the colour discrimination task condition the left index finger was placed on the "S" key on the keyboard. The central task was located at the left hand side of the touch screen monitor and targets were located to the right.

Reach to point targets were randomized between three screen locations: 15, 30 and 40 degrees into the right peripheral visual field. Targets were oval in nature and had a vertical diameter of 1.22 cm and a horizontal diameter of 1.63 cm and were all presented along the horizontal meridian of the screen. Targets were dark grey in colour (R, G & B LabView colour values were all set to 78) and were presented on a black screen. The contrast difference was great enough to make the targets easily visible to promote mapping but not so great as to create a lasting retinal afterimage upon the closure of the LCD goggles (Figure 4.2).
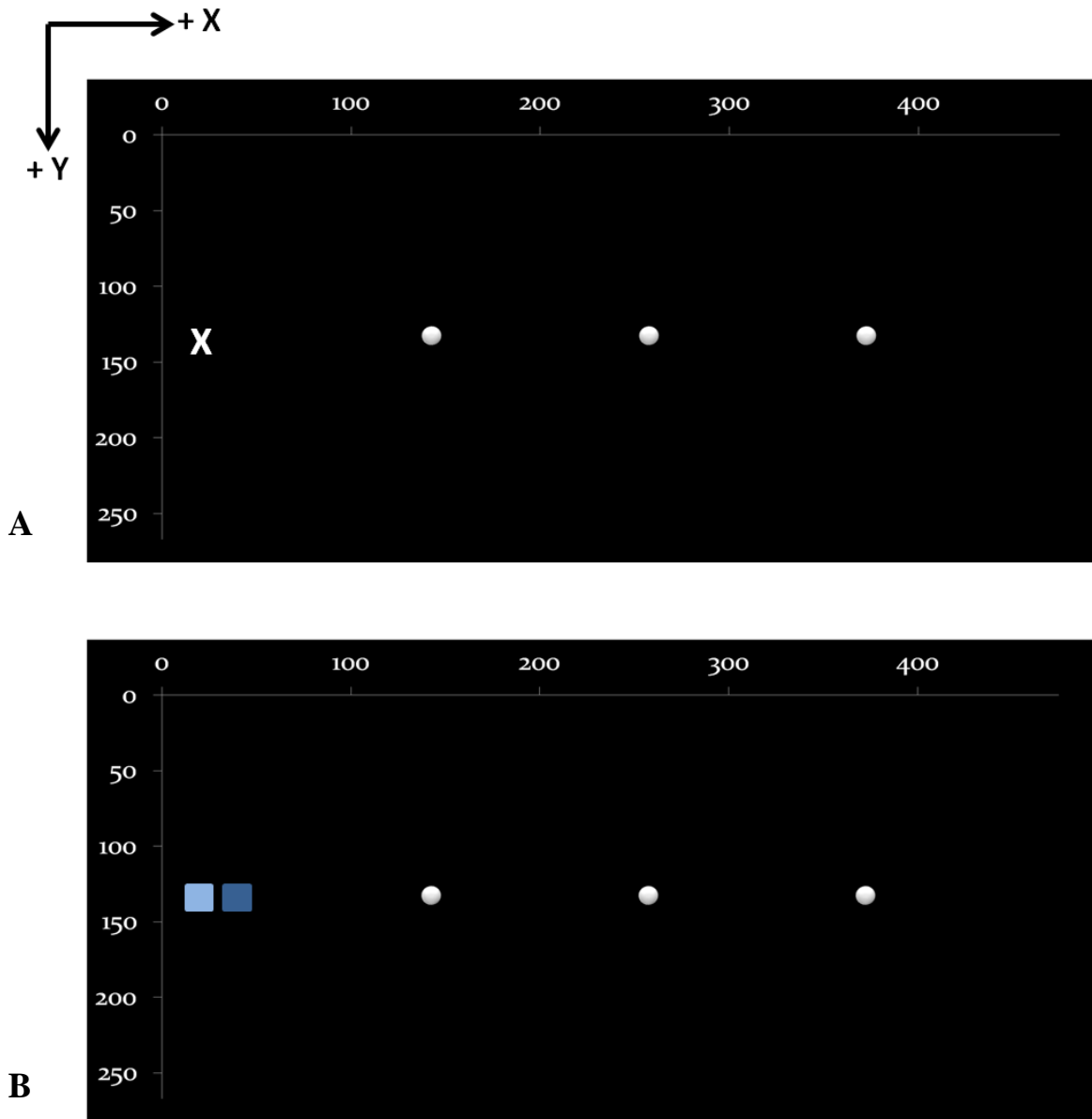
Figure 4.2: The view of the touch screen monitor for the participant for the SINGLE task (A) and the DUAL task (B). The co–ordinates designating the size of the screen were not visible to the participant. The positive directions for the X and Y directions were to the right and downwards respectively.

At the beginning of the trial, the shutters of the LCD goggles were closed. Following a random time delay of 2 to 5 seconds, the shutters opened and either the SINGLE or DUAL task was displayed. The reach–to–point target was displayed in one of the three positions between

random delays of 500 to 2000 msec following the opening of the shutters. This delay was to allow participants to become engaged in the cognitive task prior to the presentation of a target location. Participants viewed the target in the peripheral field of view for 7.5 seconds. After the 7.5 seconds in the FV condition, the central cognitive task was removed from the screen and participants received the tone to initiate their response. In the MAP condition, the shutters closed after the 7.5 seconds removing all visual feedback from the environment. There was a 100 msec delay before the tone to allow for the decay of any retinal afterimage of the target location as well as the centrally located cognitive task (Figure 4.3).

FULL VISION PARADIGM
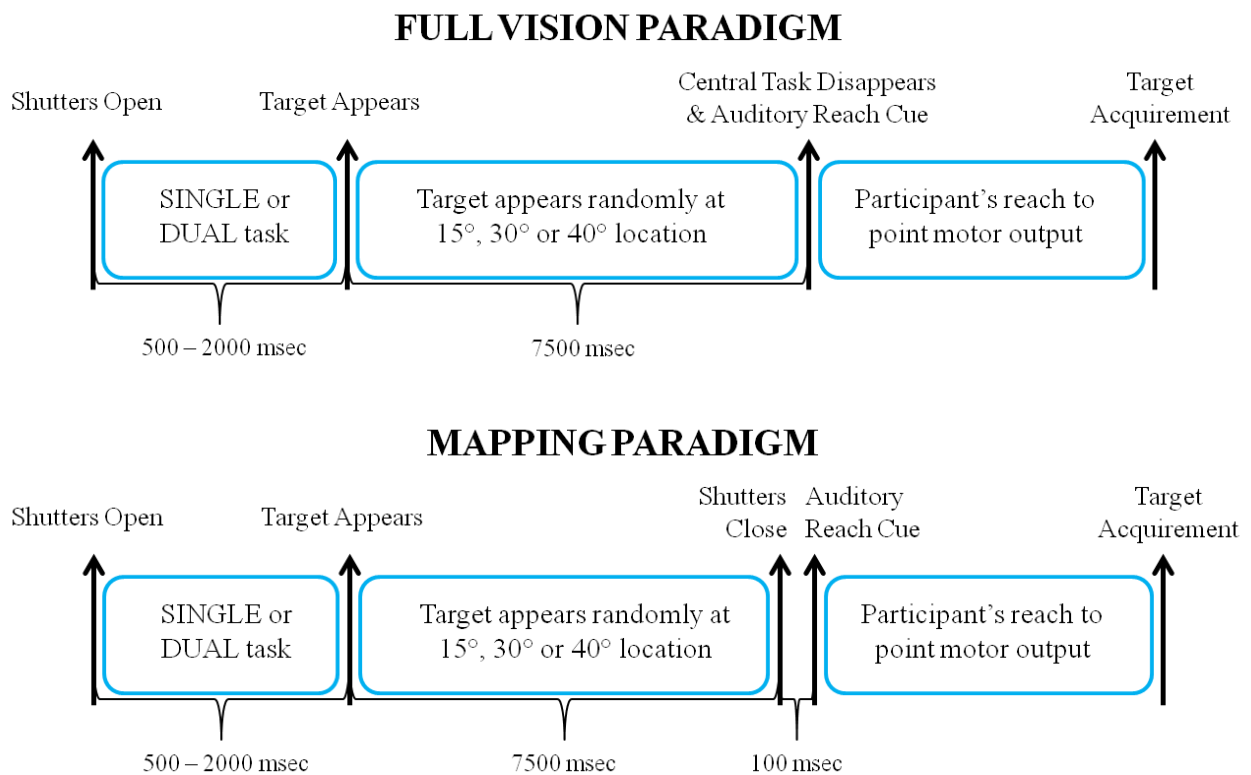
MAPPING PARADIGM

Figure 4.3: Schematic of the visual task conditions of full vision (FV) and mapping only (MAP), as well as the timing of the events within the experimental paradigm.

4.2.3 Instrumentation and Data Acquisition

A Dell ST2220T 21.5" Multi–Touch Monitor, with an average touch response time of 15 msec and a touch accuracy of ± 2.5 mm was used to present the experimental paradigm to the participant. Data were collected and analyzed with custom built LabView programs (National Instruments, Austin TX, USA). The collection program controlled the timing of the events within the protocol while allowing the experimenter to choose the visual and cognitive task conditions as well as collecting electrooculography (EOG). EOG was collected to verify gaze behaviour instructions (GRASS Technologies, West Warwick, RI, USA). Skin sites for the EOG were first abraded with NuPrep skin preparation gel and then cleaned with rubbing alcohol. The electrodes were filled with a conductive gel and were placed on the outer corner of each eye and above and below the left eye to monitor horizontal and vertical eye movement respectively. A ground electrode was placed in between the eye brows. EOG signals were band pass filtered from 0.1 – 35 Hz with a 2nd order dual pass Butterworth filter and were visually inspected for saccadic behaviour during the trials.

The acquisition program recorded the timing of the tone, the release of the space bar and when the participant made contact with the screen. The position of where the participant made contact with the screen was also recorded, and displacement with respect to target center in both the horizontal and vertical plane was calculated. The numeric values for the hues of the colour boxes were recorded to determine if they matched or were different, and the participant's reaction times to the dual task paradigm were also recorded. Separate analysis programs were made to examine participant performance (as determined by correct or incorrect responses to the colour discrimination task) during the dual task paradigm.

4.2.4 Statistical Analysis

Task comparisons were conducted using a repeated measures ANOVA [(factor 1: visual task condition (two levels); factor 2: central task condition (two levels) and factor 3: target location (three levels)]. Post hoc analysis was performed using Tukey's test with a significance value of p = 0.05. Values were averaged within task conditions within participants and statistical analysis was run on the resultant means.

4.3 Results

4.3.1 Main Effects of Vision, Task and Target on Absolute Horizontal Pointing Error

There was a main effect of visual task condition for absolute horizontal pointing error $(F_{(1,10)} = 52.23, p < 0.001)$. Post hoc comparisons revealed that there was an increase in pointing error when participants made reach to point movements with no visual feedback. Mean horizontal pointing error was 1.41 ± 1.53 cm and 3.53 ± 2.40 cm for the FV and MAP visual task conditions respectively (Figure 4.4).

There was no main effect of task difficulty on absolute horizontal pointing error $(F_{(1,10)} = 0.25, p = 0.63)$. Mean horizontal pointing error for the single task was 2.52 ± 2.14 cm and was 2.45 ± 2.41 cm for the dual task (Figure 4.5).
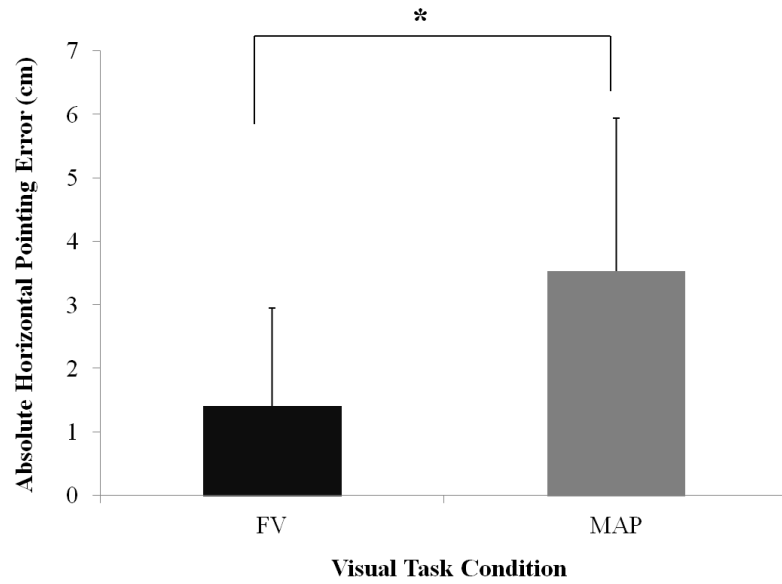
Figure 4.4: Average absolute horizontal pointing error and standard deviation comparing between the full vision (FV) and map only (MAP) visual task conditions; * denotes statistically significant difference (p<0.05).
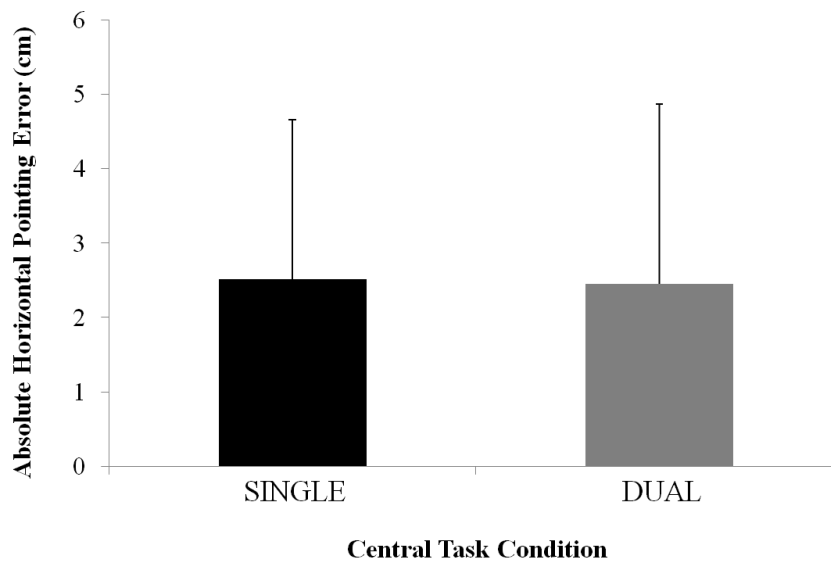
Figure 4.5: Average absolute horizontal pointing error and standard deviation comparing between the SINGLE and DUAL task conditions. There was no statistically significant difference.

There was a main effect of visual eccentricity of target location for absolute horizontal pointing error ($F_{(2,20)} = 9.97$, $p = 0.001$). Post hoc comparisons revealed that there was a significant difference in horizontal pointing error between the 15 & 30 degree target locations ($p = 0.0007$), and between the 30 & 40 degree target locations ($p = 0.032$) but no difference between the 15 & 40 degree target locations ($p = 0.24$). Mean absolute horizontal pointing error was 3.08 ± 2.63 cm, 1.81 ± 1.80 cm and 2.60 ± 2.17 cm for the 15, 30 & 40 degree target locations respectively (Figure 4.6).
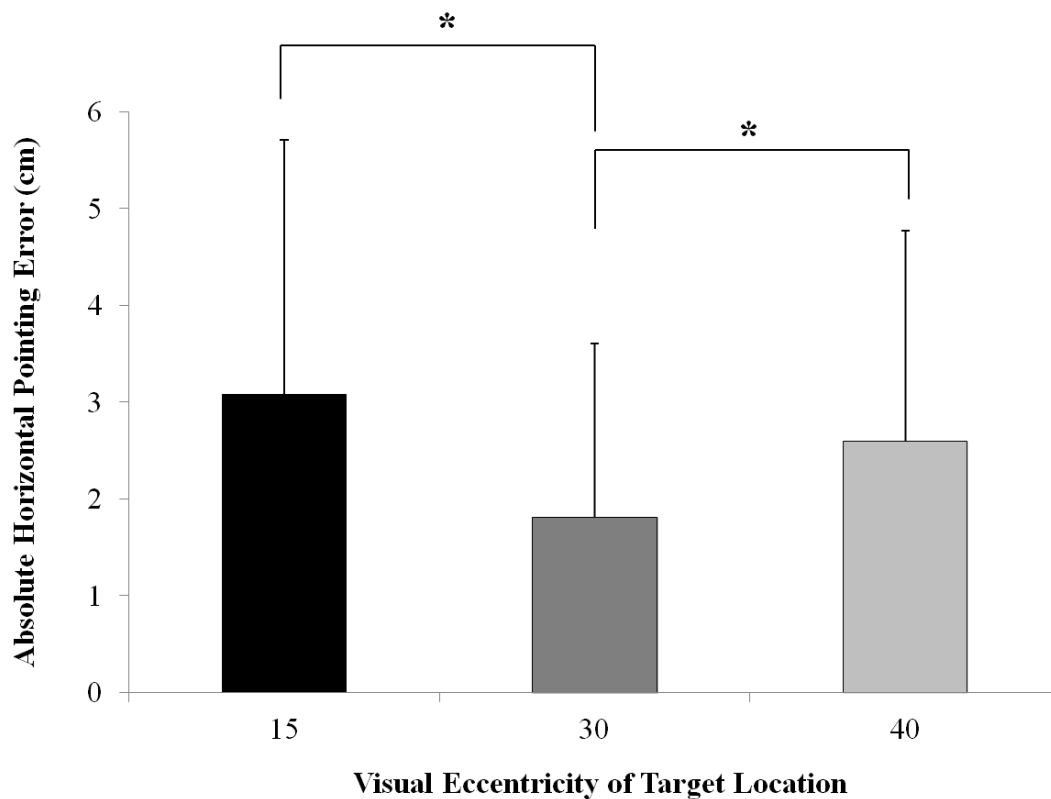
Figure 4.6: Average absolute horizontal pointing error (and standard deviation) with respect to target location comparing between the different target locations 15°, 30° and 40°; * denotes statistically significant differences.

4.3.2 Main Effects of Vision, Task and Target on Absolute Vertical Pointing Error

Interestingly, there was a similar pattern of main effects of visual, target and task condition on absolute vertical pointing error as there were on horizontal pointing error. There was a main effect of visual task condition for absolute vertical pointing error ($F_{(1,10)}$ = 9.01, p = 0.015) . Post hoc comparisons revealed that there was an increase in pointing error when participants made reach to point movements with no visual feedback. Mean vertical pointing error was 0.65 ± 0.76 cm and 2.02 ± 1.70 cm for the FV and MAP visual task conditions respectively.

There was no main effect of task difficulty on absolute vertical pointing error ($F_{(1,10)}$ = 0.41, p = 0.54). Mean vertical pointing error was 1.31 ± 1.41 cm for the single task and 1.40 ± 1.57 cm for the colour discrimination task.

There was a main effect of visual eccentricity of target location for absolute vertical pointing error ($F_{(2,20)}$ = 4.52, p = 0.026). Post hoc comparisons revealed that there was no significant difference in vertical pointing error between the 15 & 30 degree target locations (p = 0.70) or between the 30 & 40 degree target locations (p = 0.12). There was a significant difference between the 15 & 40 degree target locations (p = 0.024). Mean vertical pointing error was 1.24 ± 1.29 cm, 1.31 ± 1.49 cm and 1.50 ± 1.65 cm for the 15, 30 & 40 degree target locations respectively.

4.3.3 Variability Between Individuals

There was the potential for participants to achieve their mean absolute error (absolute error meaning error with respect to the target center) through various movement strategies. It was possible that participants executed the movement with little consistency between trials resulting in a large trial to trial variability around their central tendency. Conversely, it was possible that

participants executed the movement with great consistency resulting in small trial to trial

variability around their central tendency (see Figure 4.7 for an example). As a means of further

exploring the main effects of pointing error the average trial to trial variability around the central

tendency of pointing was examined within each individual (Figure 4.8 & 4.9). Averages were

calculated based on the resultant z vector distance (thus composing both x and y distances) from

each pointing trial with respect to the participant's mean pointing error.
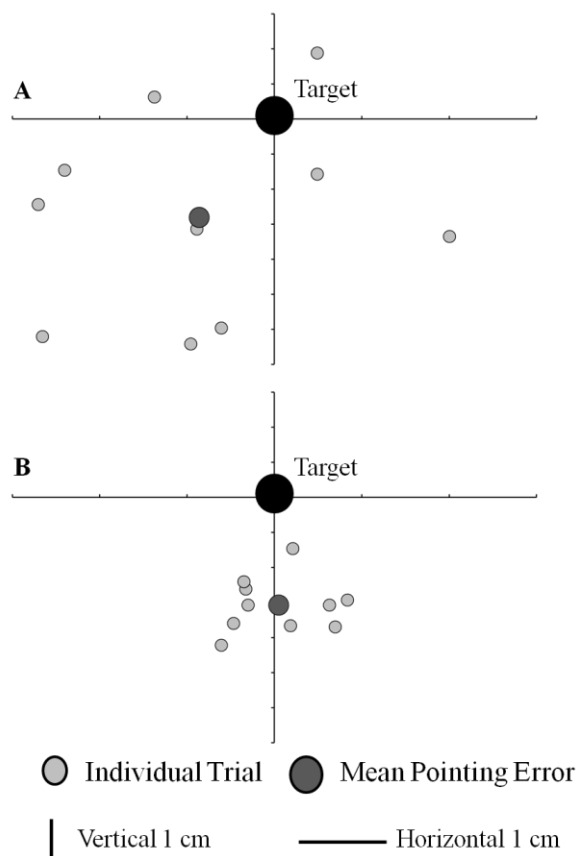
Figure 4.7: Differences in pointing errors comparing between two individuals. A – Participant 7 had large mean pointing error with respect to target center (0,0) and large trial to trial variability within each reach to point movement. B – Participant 9 also had large mean pointing error with respect to the target center (0,0) but small trial to trial variability within each reach to point movement.
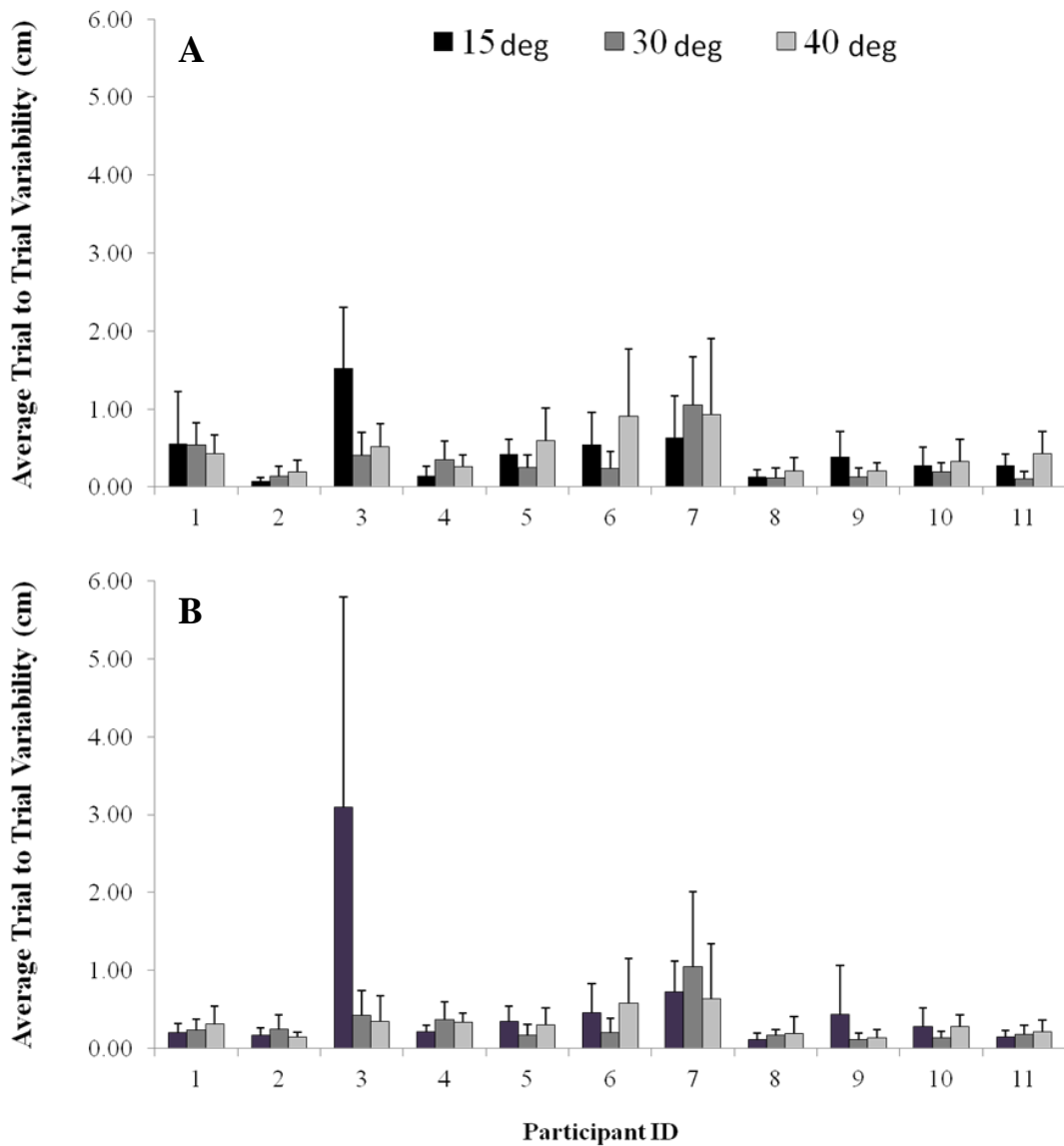
Figure 4.8: Average trial to trial variability (and standard deviation) with respect to the central tendency of the mean pointing error for each individual for (A) full vision (FV) SINGLE task and (B) FV DUAL task condition. The error represents total overall distance from their central tendency.
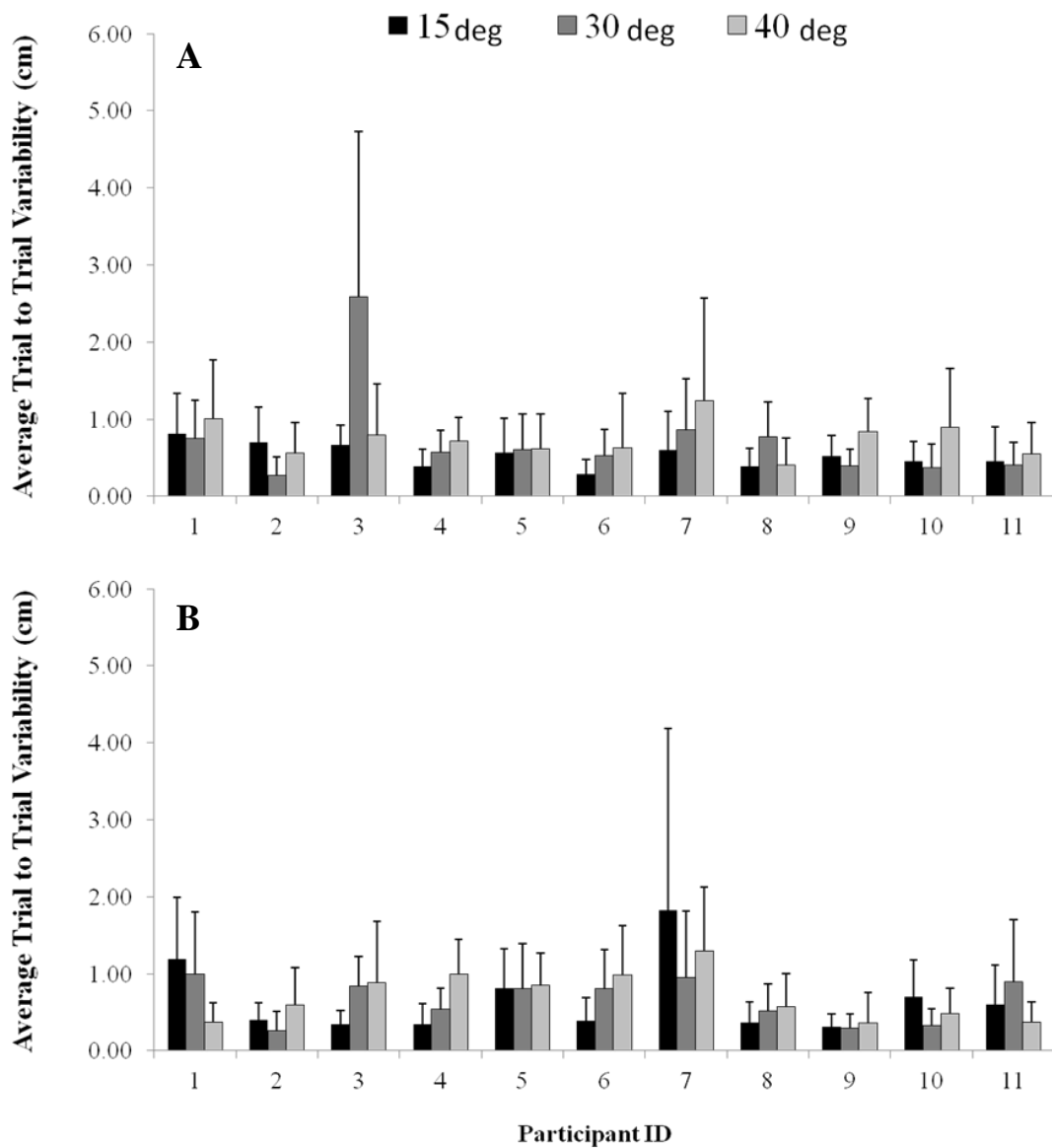
Figure 4.9: Average trial to trial variability (and standard deviation) with respect to the central tendency of the mean pointing error for each individual for (A) map only (MAP) SINGLE task and (B) MAP DUAL task condition.

4.3.4 Reaction and Movement Time

There were no main effects of vision ($F_{(1,10)} = 2.74$, $p = 0.13$), target ($F_{(2,20)} = 1.06$, $p = 0.37$) or task ($F_{(1,10)} = 2.73$, $p = 0.13$) on reaction time. There were also no main effects of vision ($F_{(1,10)} = 0.19$, $p = 0.67$), target ($F_{(2,20)} = 0.89$, $p = 0.43$) or task ($F_{(1,10)} = 1.00$, $p = 0.34$) on movement time. Mean reaction time was 553 ± 199 msec and mean movement time was 1202 ± 472 msec (Table 4.1).

Target Location	15°		30°		40°	
Task Condition	Single	Dual	Single	Dual	Single	Dual
Full Vision						
Reaction Time (msec)	554	585	554	576	570	586
Movement Time (msec)	1046	1234	1120	1236	1205	1300
Mapping						
Reaction Time (msec)	483	569	501	601	521	556
Movement Time (msec)	1182	1134	1125	1228	1254	1350

Table 4.1: Summary of average reaction time (msec) and movement time (msec) events across the three task conditions: A) visual task (full vision vs. mapping), B) target eccentricity (15°, 30° & 40°) and cognitive task (SINGLE vs. DUAL). No statistically significant differences were found between any of the task conditions.

4.3.5 Dual Task Performance

There were four possible outcomes for the performance of the colour discrimination task: participants could correctly identify a non–match (respond that the colours do not match when the shades of blue are in fact different), incorrectly identify a non–match (respond that the colours do match when the shades of blue are different), correctly identify a match (respond that the colours match when the shades of blue are the same) or incorrectly identify a match (respond that the colours match when the shades of blue are in fact different). Table 4.2 summarizes the

overall performance of the dual task as a percentage of the number of colour box stimuli that participants were to respond to. On average, participants were able to correctly identify a non – match 77% of the time while incorrectly identifying a non–match 23% of the time. On average, participants were able to correctly identify a match 25% of the time while incorrectly identifying a match 75% of the time. The overall percentage of all trials in which the colour box pairings did not match in the shade of blue was 78% while the remaining 22% of the time the colour box pairings were identical shades of blue.

Overall error rate was calculated for each individual by visual task condition and target location for further analysis. There were no main effects of vision ($F_{(1,10)} = 0.07$, $p = 0.79$) or target location ($F_{(2,20)} = 0.56$, $p = 0.58$) on the overall error rate percentage. Overall error rate percentage for the FV visual task were $36 \pm 6\%$, $35 \pm 6\%$ and $34 \pm 5\%$ for the 15°, 30° and 40° target locations respectively. Overall error rate percentage for the MAP visual task were $33 \pm 8\%$, $36 \pm 7\%$, and $34 \pm 8\%$ for the 15, 30 & 40 degree target locations respectively (Figure 4.1.1).
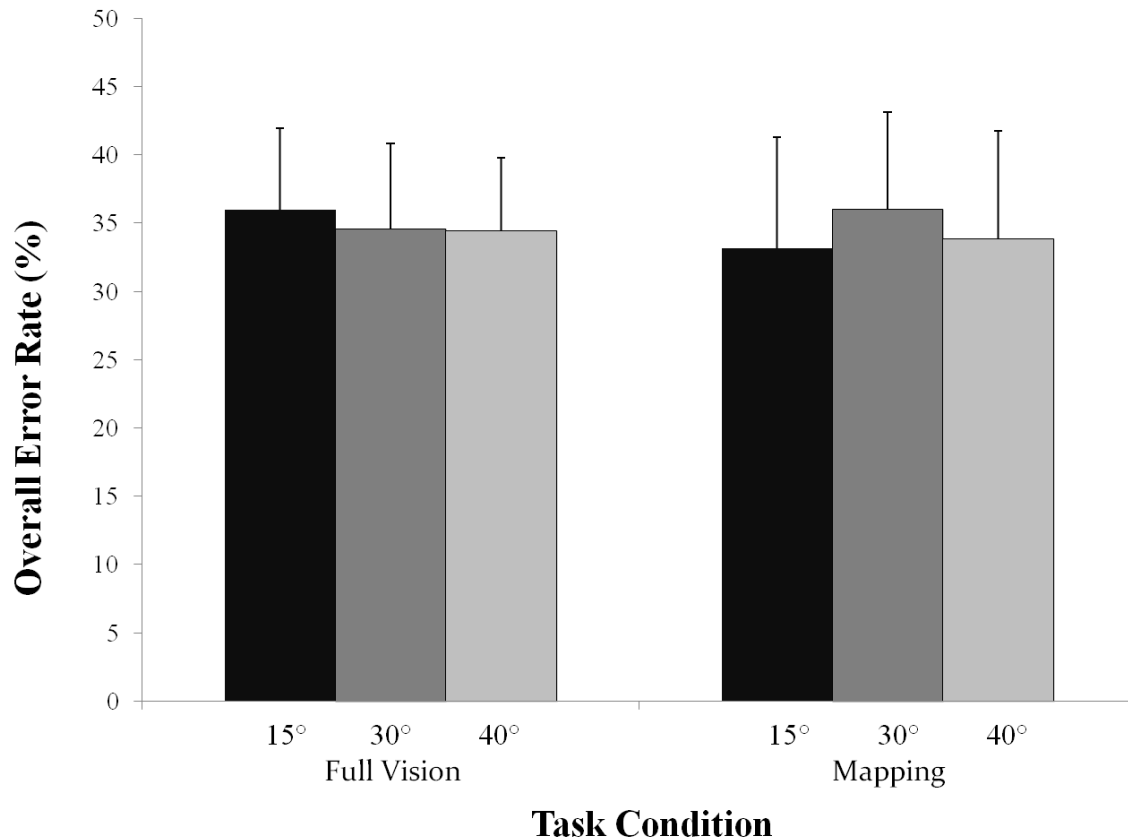
Figure 4.1.1: Average participant error rates (and standard deviation) during the colour discrimination task. No statistically significant differences were found in dual task performance between visual task condition or target location.

4.4 Discussion

The present results support the hypothesis that there would be increased absolute horizontal pointing error when reach–to–point movements were made in the absence of visual feedback. The main effect of vision was revealed within each of the target locations as well. Our results did not support the hypothesis that there would be an increase in absolute horizontal pointing error with increasing visual eccentricity. The greatest absolute horizontal error occurred for the 15 degree target, followed by the 40 degree target and lastly the 30 degree target. Our results did not support the hypothesis that there would be an increase in pointing error when

participants were asked to spatially map peripherally located targets while performing the colour discrimination task as opposed to maintaining a central fixation.

4.4.1 Influence of Vision and Target Eccentricity

It is not surprising that mean pointing error was greater when participants made reach–to–point movements in the absence of online visual feedback. It is well established that the terminal accuracy of reaching to grasp or point is greater when participants have online visual feedback throughout movement execution (Binsted et al., 2006; Gonzalez – Alvarez et al., 2007; Westwood et al., 2003). It was interesting to note that no differences were present in the absolute horizontal pointing error between the 15 & 40 degree target locations. When mean pointing error was plotted relative to target center, thus accounting for directional error, we found that individuals tended to overshoot the 15 degree target whereas they tended to undershoot the 40 degree target in the horizontal direction. Another unexpected finding was that the absolute vertical pointing error was also influenced by visual feedback, such that pointing error increased as a function of target eccentricity with significant differences arising between the 15 and 40 degree target locations. We did not expect to see any difference in vertical pointing error as the targets were presented along the same horizontal meridian of the touch screen monitor. Again, when relative means were examined, it was found that participants tended to undershoot all target locations within the vertical plane of the screen in a progressive manner (i.e. they tended to point beneath the target for all three target locations, such that the relative distance beneath the target was greatest for the 40 degree target, then the 30 degree target and finally the 15 degree target).

Westwood et al., (2003) suggest that memory guided reaches tend to undershoot target location for two possible reasons. Firstly, target undershoot may result from visuospatial memory

decay of the immediate environment as a function of the delay between when vision is occluded

and when the participant initiates the movement. The other possibility is that target undershoot

may be a conservative strategy so as to avoid bumping into or knocking over the intended object

(Gonzalez – Alvarez et al., 2007; Westwood et al., 2003). Similar reasoning theorizes increased

maximum grip aperture that is observed in open-loop reach–to–grasp paradigms (Connolly &

Goodale, 1999). However, in our experimental paradigm, participants performed reach–to–point

movements to a target on a touch screen monitor, thus there was no consequence with respect to

overshooting or undershooting the target in either the horizontal or vertical direction. In contrast,

there is the potential for severe consequences should a target handhold not be grasped in a

manner that would enable re–stabilization in the case of compensatory balance reactions. In fact,

it has been observed in compensatory reach–to–grasp studies that participants will adopt a

strategy that enables them to hook their hand around a target handle in a swiping motion as

opposed to performing a traditional grasping motion (Gage et al., 2007).

Another possibility we suggest is that endpoint reaching errors may result from an

inaccurate internal representation of the environmental surround due to encoding errors. A

common, real–world example utilized in the literature to emphasize the importance of

remembered visual space is a reach for a cup of coffee. Individuals are able to gaze from their

computer screen to their coffee mug and back to their computer screen *before* they initiate the

reach for their coffee mug. Thompson & Henriques, 2011, have referred to this as "predictive

remapping of remembered visual space" (pg. 820) and argue that the reach to the coffee mug is

done based on a remembered representation of visual space as the mug's location is now

peripherally located with respect to foveal vision. A predominant theory in the literature is that

the eyes lead the hand when executing reaching tasks, such that individuals will first gaze to the

intended target and foveate on it prior to initiating a reach towards it. However, in many circumstances, the reaching motion is initiated prior to a saccade towards the target, such that the hand starts to move towards a target while the target is still in the peripheral field of view (Brouwer & Knill, 2009). During the movement of the upper limb, a saccade is carried out in order to bring the target object into foveal capture. Due to the rapidity of saccades, the eyes bring the target into foveal capture before the hand reaches the target (Brouwer & Knill, 2009) This suggests then that the details gained through central vision are important for the online control of the reaching movement, but may not be as important in the planning of the reach–to–grasp / point motor program (Brouwer & Knill, 2009). We are able to recognize and locate a target object with peripheral vision and undergo a visuomotor transformation in order to initiate a reach towards it. Under normal circumstances, individuals may initiate saccades to the target to allow for greater endpoint accuracy control of grasping and / or pointing movements. In this experiment, the endpoint target for the reach to point task was small, thus demanding of spatial accuracy. However, in compensatory reach to grasp tasks target handles are usually quite large, allowing for greater variation in terminal accuracy of the hand while still providing effective re–stabilization. This is also true of most everyday scenarios, such that handrails tend to be large so as to permit grasping, and in some cases are quite continuous in nature (e.g. railing for stairs or overhead railings on subways) allowing individual's greater probability of making contact in order to support themselves.

But what about when individuals are required to encode targets that are located in the peripheral visual field without having previously foveated on the target or target area? Duhamel et al., (1992) demonstrated that activity occurs in neurons that constitute what will be the new receptive field for foveal vision prior to the actual initiation of a saccade to the new target area.

Individuals may in fact plan a saccade to a new target area while suppressing its execution during experimental paradigms in which participants are asked to refrain from foveating on targets so as to keep the target in the peripheral visual field. This may increase activity in neurons that would be expected to become active once the saccade has been initiated, and may also aid in the ability to map peripherally located targets (Colby et al., 1995). It may also be a mechanism for encoding errors for peripherally located targets. It is common for individuals to make multiple saccades to a peripherally located target (Harris, 1994). Thus, if individuals tend to undershoot their initial saccade to a target and are required to make a second saccade, it is possible that as participants planned a saccade to the 40 degree target that initial saccade motor program would have undershot the target location. Thus, the new receptive field in saccade planning would fall short of target location, and that may be why participants had a tendency to undershoot the initial target location at 40 degrees.

It is also possible that the error was not due to the encoding process, but rather the transformation of information between multiple reference frames. There is a prominent view in the literature that the encoding, storage and updating of target locations that are relevant for eye and / or arm movement is done in a gaze–centered reference frame as a function of eye movement (Thompson & Henriques, 2011). Predictive efference copies of oculomotor and upper limb movements are compared with the reafference of the ongoing movement to allow for modification of limb trajectory (Thompson & Henriques, 2011). This enables a continuous conversion of target location from a retinotopic reference frame to head–centered and limb–centered reference frames (Thompson & Henriques, 2011). Spatial transformations of visuospatial information between these multiple reference frames may result in incomplete transformation if the movements are performed rapidly (Binsted et al., 2006). Thus, limb

movements would be largely dictated by the saccadic updating that occurs, and would be subject to any errors in saccades (Binsted et al., 2006).

4.4.2 Influence of Attention

Contrary to our predictions, there was no effect of the central cognitive task condition on mean absolute pointing error. The lack of effect between the two different task demands during the encoding process may be accounted for with several explanations. The first is that a lack of effect of central task condition on end point reaching error may suggest that the mapping of peripherally located targets is a highly automatic process. The process of mapping said targets may be highly influenced by bottom–up processing of objects in the environment based on their salience and / or whether or not they may have any behavioural relevance (Buneo & Andersen, 2006). A second possibility is that the fixation task itself required top–down attentional resources so as to keep the eyes focused on the fixation point thereby suppressing saccades to the target. Conversely, the colour discrimination task itself may not have been as demanding of top–down attentional resources as anticipated, and thus did not demonstrate any difference when compared to the fixation task. Finally, it is also possible that both the fixation task and the colour discrimination task required similar attentional demands thus revealing no difference in pointing error as a result of the encoding process. This may also suggest that participants did not disengage attentional resources from the central colour discrimination task in order to use the same executive resources for mapping the peripheral location of the target.

It has been demonstrated the FFOV can vary based on the demands of the task(s) that individuals are asked to perform. The FFOV can be quite broad when performing a single, simple task such as a target detection task, but can decrease with the addition of a secondary cognitive task or other environmental distracters (Coeckelbergh et al., 2004; Scalf et al., 2007). It

has also been demonstrated that young, healthy individuals do not incur the same performance deficits in FFOV dual task paradigms as do older adults (Ball & Owsley, 1993; Coeckelbergh et al., 2004; Scalf et al., 2007). Coeckelbergh et al. (2004) demonstrated that younger individuals do not make as many saccades as older individuals when scanning for a target amidst distracters. They suggest that the younger individuals do not experience the same decrement in FFOV as older individuals and further suggest that younger individuals may have been able to implement a greater amount of parallel visual processing over a wider FFOV while older individuals had to visually scan for the target in a serial processing manner (Coeckelbergh et al., 2004). As previously stated, the central cognitive tasks in this experiment may have had similar attentional requirements or may not have been as taxing to attentional resources as we had anticipated. In addition, the reach–to–point target was the only target presented to the participant. No distracter target locations were made available which may have in turn increased attention demands on the participants. Furthermore, the presentation time of the reach–to–point target in this experiment was quite long at 7500 msec. A long target presentation time was chose to ensure that A) participants did have ample time to map a peripherally located target (i.e. we did not want reach–to–point errors to be due to insufficient mapping time) and B) individuals were mapping while engaged in a central cognitive task. These factors together may have resulted in minimal decreases to FFOV thus enabling participants to perceive and map the peripherally located targets albeit miss–localizing their location.

Perhaps the colour discrimination task did not interfere with the participant's ability to perceive and encode the peripherally located targets due to the initiation of the movement immediately after the onset of the cue to move. Perhaps the attention task affects the transformation of the visuospatial information into a memory store, such that delayed reach–to–

70

point movements may have shown an effect based on the central task condition. It has been suggested that the stored representation of the visuospatial surround decays within approximately 2 – 3 seconds after the removal of visual feedback (Binsted et al., 2006; Westwood et al., 2003). Binsted et al. (2006) found increases in error with Fitts' Tapping Task 500 msec after the occlusion of the targeted area, but that this error remained at a plateau for 2 – 3 seconds after the initial increase in variability. After the 2 – 3 second plateau, endpoint variability continued to increase as a function of time, suggesting that for the time frame of 2 – 3 seconds this internal representation can remain fairly stable, followed by a rapid decay as a result of lack of visual feedback (Binsted et al., 2006). In our experiment, participants initiated the reaching movement coinciding with visual occlusion, and in balance reactions, responses are immediate as delays in response initiation have the potential to lead to a fall and subsequent injury. In other words, it may be that the colour discrimination task did not affect the ability to perceive and encode the peripherally located target, but it may affect the ability to code and store that location into memory for later use or may interfere with the planning and execution of the required movement.

The colour discrimination task was chosen specifically because it is a visual attention task, not a working memory task (such as an N – back) dual task paradigm. It is possible that a memory related task would result in differences in dual task performance when mapping a peripherally located target and / or result in greater differences in pointing error than an attention task. Capacity limits on short term memory may place limitations on the ability to encode potential target locations from the peripheral visual field into short term visual memory stores (Brouwer & Knill, 2009). The hippocampus has been demonstrated to have a major role in both memory and cognitive mapping functions (Smith & Mizumori, 2006). It has also been suggested that the hippocampus is involved in the mental reconstruction of the environment, and that

hippocampal neurons may also alter their firing patterns based on task demands and problem solving strategies employed by individuals (Smith & Mizumori, 2006).

4.4.3 Reaction and Movement Time

No difference in reaction time suggests that participants adhered to instructions and began their reach in response to the auditory cue. No difference in movement time suggests that participants did not slow their reaching movement when reliant on stored visuospatial information or when performing a concurrent secondary task. On one hand, it may be expected that movement time would be longer in the full vision condition, as participants may slow their movement in order to use the available online visual feedback gathered from the peripheral visual field in order to make corrections to limb trajectory to ensure correct pointing to the target. On the other hand, it may be expected that when reaching–to–point based on a stored visuospatial representation, participants may slow their reaching movement in order to reconstruct a mental image in order to make their reaching more accurate. Conversely, the memory based reaches may have been expected to be faster so that participants could utilize the visuospatial representation as quickly as possible in order to prevent map decay or potential pointing errors based on encoding error. There was also no decrement in reaction time or movement time as a result of the colour discrimination task. This suggests that the performance of the secondary visual attention task may not have affected the ability of the participant to plan the motor program required for the reach to point task.

4.4.4 Individual Differences & Strategies

What was striking were the large differences in trial to trial variability that were apparent between individuals as well as within individuals, comparing between visual condition, central task condition and target location. Some have high average error with respect to the center of the

target and high trial to trial variability with respect to their own central tendency (for example, participants 3, 7 & 10) while others have high average error with respect to the center of the target and low trial to trial variability with respect to their central own tendency (for example, participants 9 & 11). Importantly there was no apparent relationship of speed of movement execution and reach–to–point performance between these individuals. It is typically assumed that a participant set of young, healthy individuals will be homogeneous in nature – in both physical and cognitive capacities – and that these individuals will perform the task in a similar nature. However, the results from this study suggest that individual strategies for task performance may differ among this group.

4.4.5 Limitations

The results from the current study may be difficult to extrapolate to a compensatory balance paradigm. However, the complexities associated with balance paradigms also have the potential to conflict with what we would have expected to find with regards to attention allocation for the purposes of visuospatial mapping. As a result, it was deemed necessary in this initial stage to explore these relationships in a non–balance task. The differences between this work and the potential application to balance are likely largely associated with the differences in the consequence of errors. The consequences of end point error in this experiment are substantially different from endpoint error in a balance experiment. In compensatory balance studies, failure to make contact with the target area to re–stabilize likely leads to heightened arousal and motivation so as not to "fall" in subsequent trials (Lakhani et al., 2011; Sibley et al., 2009). The potential threat does influence speed of movement and may affect attention allocation, movement strategies and end point errors in a different manner than volitional movement with respect to movement execution based on an internal visuospatial map.

It is also possible that difference in attention allocation between the two central cognitive tasks did exist, but that the measurement used (error rate) does not provide any information based on differences in cortical activity between the simple fixation task and the colour discrimination task. A potential adjunct would be to include collection of electroencephalography (EEG) while performing the cognitive task only (no mapping of reach to point targets) to examine any differences in cortical activity. Another potential avenue to explore would be to have participants engage in the same cognitive tasks but reach–to–grasp an object as opposed to reaching to point to the touch screen. This may increase arousal levels somewhat, as there would be increased consequence to the movement (bumping into the object or knocking it over) and would also provide sensory feedback about success of the movement.

4.5 Conclusions

The results of this study provide support for the ability to create visuospatial maps with peripheral visual information prior to the onset of a stimulus and their use in volitional reach–to–point movements. The ability to encode a peripherally located target into an internal visuospatial representation for the purpose of immediate action appears to require minimal visual attentional resources. Participants also appear to be quite variable in their movement, both between and within individuals, based on the task demands of the trial. Future research may aim to examine potential differences the allocation of attention between the two cognitive tasks used in this study in a compensatory balance reaction paradigm when the consequences of the movement may be more behaviourally relevant to the participant. Another potential area of focus is to implement a task that has a greater requirement on visuospatial working memory as opposed to visual attention and examine those effects on mapping peripherally located targets in both volitional and compensatory reach–to–point / reach–to–grasp paradigms.

Chapter 5: General Discussion

5.1 General Discussion

The purpose of this thesis was to examine the influence of peripheral vision on the control of reach–to–point and reach–to–grasp movements. The work also explored the potential attentional requirements in forming intrinsic visuospatial maps of the environmental surround prior to the onset of upper limb movements. Specifically, mapping the environment with peripheral visual information may be an important on–going process that is necessary for effective re–stabilization in compensatory reach–to–grasp reactions. The importance likely relates to the naturally unexpected nature of perturbations to stability and the tight temporal timelines associated with the initiation and execution of the responses. This limits the likely ability to direct and use foveal vision to guide rapid reach–to–grasp reactions. In conjunction with the use of incoming peripheral visual information is whether or not individuals are able to map salient environmental features regarding spatial locations of objects without having previously foveated on these objects. Results from the first study revealed that healthy young adults are able to form and use an intrinsic visuospatial map of the environmental surround that has been created from the peripheral visual field. The second experiment found that the ability of individuals to visuospatially map behaviourally relevant features of their environment appears to be automatic in nature.

In order to successfully recapture stability, compensatory reach–to–grasp reactions must be directed towards a target handhold in order to be effective. Due to the temporal constraints associated with compensatory balance reactions, it may be imperative that these reaches are target specific from reach initiation, as making corrections to reach trajectories in–flight may

serve to delay contact with a potential stabilizing object. Importantly, this work revealed that individuals are able to use sensory information gathered from the peripheral visual field for the purposes of mapping and thus planning the initial trajectory of the wrist in a compensatory reach–to–grasp reactions, re–affirming that visuospatial information gathered prior to a perturbation can be incorporated into the early stages of a compensatory balance reaction. However, as visual eccentricity increases, strategies may be adopted to increase the likelihood of successful handle contact such as a broad swiping motion towards the handle as well as hooking the handle with a wide open hand as opposed to a stereotypical grasping motion (Gage et al., 2007). However, it should be noted that this was not just about guiding the initiation of the reach–to–grasp response but also about controlling reaching with online visual feedback gathered after perturbation onset. A further novel finding in this thesis was that individuals are also able to successfully re–stabilize themselves with a compensatory reach–to–grasp reaction when no vision had been available prior to perturbation onset, thus entirely dependent on online visual feedback. Participants adopted the strategy of reaching towards the middle target and were able to use online visual feedback to make successful corrections to trajectory even though the speed of the movement was extremely rapid.

This work also highlights the challenges associated with assessing the attention components of visuospatially mapping the environment for the purposes of immediate action. The task(s) chosen to engage executive function and the behavioural way in which participants are required to respond to it may impact peripheral mapping ability in different ways. A secondary auditory attention task could presumably influence the ability to map peripherally located reach–to–grasp targets in a different manner than a visuospatial working memory task assuming that the process of mapping was dependent on some attention resources. There may

also be an influence of how the participant is asked to respond: verbally vs. a mouse click; continuously throughout a trial vs. at the end of a trial. Therefore, the results from the second study provide a very basic insight into the methodological considerations for future dual task paradigms relating to reactive balance control.

5.2 Future Directions

The studies contained within this thesis provide the basic framework for the knowledge that individuals are able to visuospatially map peripherally located targets for the purposes of immediate action. Future studies may explore other variables associated with mapping ability.

One possible study could examine the timing parameters that enable individuals to map their environment. The two studies in this work allowed participants a minimum of 2 seconds to map the target location within their environment. The minimum time frame that people require to map peripherally located targets us currently unknown. Further still, is how often are these maps updated? We presume that they are updated on a second to second basis, when in fact they may be updated much more frequently, as visual feedback is continuous in nature, or conversely, may only need to be updated when something within the immediate environment has changed, such as movement of objects and / or the observer within that environment.

Gaining insight into the mapping ability of other populations, specifically older individuals and those with neurological impairment(s) is another avenue for future directions for this work. If visuospatial mapping with peripheral visual information is an important component for the neural control of balance, then examining mapping abilities of individuals who may have an impaired ability to utilize peripheral visual information may provide us with insights into the adaptive strategies these individuals use. For example, it may be of interest to compare upper

limb trajectories between a group of individuals with cataracts (little peripheral visual information available) and a group of individuals with macular degeneration (only peripheral visual information available). Gaining greater insight into the use of peripheral visual information for the purposes of mapping for upper limb compensatory responses within a population that is more likely to fall (elderly, stroke patients etc.) may provide better insight into designing and implementing rehabilitative and fall prevention programs for these individuals.

5.3 Conclusions

This thesis investigated the role of peripheral vision and associated attentional requirements for the purposes of immediate action. Both compensatory and volitional reaching movements were assessed in healthy, young adults under different visual feedback conditions and executive function requirements. It was observed that these individuals are able to visually map a peripherally located target without having previously foveated on the target and that the ability to map this target location appears to be an automatic process. The findings from this thesis may lead to future contributions to fall prevention and stroke rehabilitation programs through implementing cognitive visuospatial training.

References

Alfano, P. L., & Michel, G. F. (1990). Restricting the field of view: Perceptual and performance

    effects. *Perceptual and Motor Skills, 70*, 35-45.

Baldauf, D., & Deubel, H. (2010). Attentional landscapes in reaching and grasping. *Vision*

    Research, 50, 999-1013.

Ball, K., & Owsley, C. (1993). The useful field of view test: A new technique for evaluating age-

    related declines in visual function. *Journal of the American Optometric Association, 64*, 71-

    79.

Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and visual

    search: Expanding the useful field of view. *Journal of the Optical Society of America, 5*,

    2210-2219.

Bédard, P., & Proteau, L. (2004). On-line vs. off-line utilization of peripheral visual afferent

    information to ensure spatial accuracy of goal-directed movements. *Experimental Brain*

    Research, 158, 75-85.

Berencsi, A., Ishihara, M., & Imanaka, K. (2005). The functional role of central and peripheral

    vision in the control of posture. *Human Movement Science, 24*, 689-709.

Binsted, G., Rolheiser, T. M., & Chua, R. (2006). Decay in visuomotor representations during

    manual aiming. *Journal of Motor Behavior, 38*, 82-87.

Black, A., & Wood, J. (2005). Vision and falls. *Clinical and Experimental Optometry, 88*, 212-

    222.

Blouin, J., Teasdale, N., Bard, C., & Fleury, M. (1993). Directional control of rapid arm

    movements: The role of the kinetic visual feedback system. *Canadian Journal of*

    Experimental Psychology, 47, 678-696.

Bouisset, S., & Do, M. (2008). Posture, dynamic stability, and voluntary movement.

    Neurophysiologie Clinique / Clinical Neurophysiology, 38, 345-362.

Brauer, S. G., Woollacott, M., & Shumway-Cook, A. (2002). The influence of a concurrent

    cognitive task on the compensatory stepping response to a perturbation in balance-impaired

    and healthy elders. *Gait and Posture, 15*, 83-93.

Brouwer, A., & Knill, D. C. (2009). Humans use visual and remembered information about

    object location to plan pointing movements. *Journal of Vision, 9*, 24.1-2419.

Brown, L. A., Sleik, R. J., Polych, M. A., & Gage, W. H. (2002). Is the prioritization of postural

    control altered in conditions of postural threat in younger and older adults? *Journal of*

    Gerontology, 57, M785-M792.

Buneo, C. A., & Andersen, R. A. (2006). The posterior parietal cortex: Sensorimotor interface

    for the planning and online control of visually guided movements. *Neuropsychologia,*

    44(13), 2594-2606.

Cheng, K. C., McKay, S. M., King, E. C., Tung, J. Y., Lee, T. A., Scovil, C. Y., et al. (2009).

    The moveable handhold: A new paradigm to study visual contributions to the control of

    balance-recovery reactions. *Gait & Posture, 29*, 339-342.

Clavagnier, S., Prado, J., Kennedy, H., & Perenin, M. (2007). How humans reach: Distinct

cortical systems for central and peripheral vision. *The Neuroscientist, 13*, 22-27.

Coeckelbergh, T. R. M., Cornelissen, F. W., Brouwer, W. H., & Kooijman, A. C. (2004). Age-

related changes in the functional visual field: Further evidence for an inverse age ×

eccentricity effect. *The Journals of Gerontology Series B: Psychological Sciences and*

Social Sciences, 59, P11-P18.

Colby, C. L., Duhamel, J., & Goldberg, M. E. (1995). Oculocentric spatial representation in

parietal cortex. *Cerebral Cortex, 5*, 470-481.

Connolly, J. D., & Goodale, M. A. (1999). The role of visual feedback of hand position in the

control of manual prehension. *Experimental Brain Research, 125*, 281-286.

Duhamel, J. R., Colby, C. L., & Goldberg, M. E. (1992). The updating of the representation of

visual space in parietal cortex by intended eye movements. *Science, 255*, 90-92.

Franchak, J. M., & Adolph, K. E. (2010). Visually guided navigation: Head-mounted eye-

tracking of natural locomotion in children and adults. *Vision Research, 50*, 2766-2774.

Frank, J. S., & Earl, M. (1990). Coordination of posture and movement. *Physical Therapy, 70*,

855-863.

Frey, H. P., Kelly, S. P., Lalor, E. C., & Foxe, J. J. (2010). Early spatial attentional modulation of

inputs to the fovea. *The Journal of Neuroscience, 30*, 4547-4551.

Gage, W. H., Zabjeck, K. F., Hill, S. W., & McIlroy, W. E. (2007). Parallels in control of
voluntary and perturbation-evoked reach-to-grasp movements: EMG and kinematics.
Experimental Brain Research, 181, 627-637.

Ghafouri, M., McIlroy, W. E., & Maki, B. E. (2004). Initiation of rapid reach-and-grasp balance
reactions: Is a pre-formed visuospatial map used in controlling the initial arm trajectory?
Experimental Brain Research, 155, 532-536.

González-Alvarez, C., Subramanian, A., & Pardhan, S. (2007). Reaching and grasping with
restricted peripheral vision. *Ophthalmic and Physiological Optics, 27*, 265-274.

Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action.
Trends in Neurosciences, 15, 20-25.

Hall, N. J., & Colby, C. L. (2011). Remapping for visual stability. *Philisophical Transactions of
the Royal Society B: Biological Sciences, 366*, 528-539.

Harris, C. M. (1995). Does saccadic undershoot minimize saccadic flight-time? A monte-carlo
study. *Vision Research, 35*, 691-701.

Horak, F. B., & Nashner, L. M. (1986). Central programming of postural movements:
Adaptation to altered support-surface configurations. *Journal of Neurophysiology, 55*, 1369-
1381.

Horak, F. B. (1987). Clinical measurement of postural control in adults. *Physical Therapy, 67*,
1881-1885.

Horak, F. B. (2006). Postural orientation and equilibrium: What do we need to know about neural control of balance to prevent falls? *Age and Ageing, 35*, ii7-ii11.

Horak, F. B. (2010). Postural compensation for vestibular loss and implications for rehabilitation. *Restorative Neurology and Neuroscience, 28*, 53-64.

Horak, F. B., Henry, S., M., & Shumway-Cook, A. (1997). Postural perturbations: New insights for treatment of balance disorders. *Physical Therapy, 77*, 517-533.

Inglis, J., Horak, F., Shupert, C., & Jones-Rycewicz, C. (1994). The importance of somatosensory information in triggering and scaling automatic postural responses in humans. *Experimental Brain Research, 101*, 159-164.

Jacobs, J. V., & Horak, F. B. (2007). Cortical control of postural responses. *Journal of Neural Transmission, 114*, 1339-1348.

King, E. C., Lee, T. A., McKay, S. M., Scovil, C. Y., Peters, A. L., Pratt, J., et al. (2011). Does the "eyes lead the hand" principle apply to reach-to-grasp movements evoked by unexpected balance perturbations? *Human Movement Science, 30*, 368-383.

King, E., McKay, S., Cheng, K., & Maki, B. (2010). The use of peripheral vision to guide perturbation-evoked reach-to-grasp balance-recovery reactions. *Experimental Brain Research, 207*, 105-118.

Kravitz, D. J., Saleem, K. S., Baker, C. I., & Mishkin, M. (2011). A neural framework for visuospatial processing. *Nature Reviews. Neuroscience, 12*, 217-230.

Lakhani, B., Van Ooteghem, K., Miyasike-daSilva, V., Akram, S., Mansfield, A., & McIlroy, W. E. (2011). Does the movement matter? determinants of the latency of temporally urgent motor reactions. *Brain Research, 1416*, 35-43.

Land, M., F. (2009). Vision, eye movements, and natural behavior. *Visual Neuroscience, 26*, 51-62.

Leff, A. (2004). A historical review of the representation of the visual field in primary visual cortex with special reference to the neural mechanisms underlying macular sparing. *Brain and Language, 88*, 268-278.

Lephart, S., M., Pincivero, D., M., & Rozzi, S. L. (1998). Proprioception of the ankle and knee. *Sports Medicine, 25*, 149-155.

Lord, S. R. (2006). Visual risk factors for falls in older people. *Age and Ageing, 35*, ii42-ii45.

Maki, B. E., & McIlroy, W. E. (2005). Change-in-support balance reactions in older persons: An emerging research area of clinical importance. *Neurologic Clinics, 23*, 751-783.

Maki, B. E., & McIlroy, W. E. (2007). Cognitive demands and cortical control of human balance-recovery reactions. *Journal of Neural Transmission, 114*, 1279-1296.

Maki, B. E., McIlroy, W. E., & Fernie, G. R. (2003). Change-in-support reactions for balance recovery. *Engineering in Medicine and Biology Magazine, IEEE, 22*, 20-26.

Maki, B. E., & McIlroy, W. E. (1997). The role of limb movements in maintaining upright stance: The "change - in - support" strategy. *Physical Therapy, 77*, 488-507.

Maki, B. E., & McIlroy, W. E. (2006). Control of rapid limb movements for balance recovery: Age-related changes and implications for fall prevention. *Age and Ageing, 35*, ii12-ii18.

Marigold, D. S., Weerdesteyn, V., Patla, A. E., & Duysens, J. (2007). Keep looking ahead? re-direction of visual fixation does not always occur during an unpredictable obstacle avoidance task. *Experimental Brain Research, 176*, 32-42.

Massion, J. (1992). Movement, posture and equilibrium: Interaction and coordination. *Progress in Neurobiology, 38*, 35-56.

McIlroy, W. E., & Maki, B. E. (1993). Do anticipatory postural adjustments precede compensatory stepping reactions evoked by perturbation? *Neuroscience Letters, 164*, 199-202.

McIlroy, W. E., & Maki, B. E. (1995). Early activation of arm muscles follows external perturbation of upright stance. *Neuroscience Letters, 184*(3), 177-180.

Medendorp, W. P., Beurze, S. M., Van Pelt, S., & Van Der Werf, J. (2008). Behavioral and cortical mechanisms for spatial coding and action planning. *Cortex, 44*, 587-597.

Mergner, T., & Rosemeier, T. (1998). Interaction of vestibular, somatosensory and visual signals for postural control and motion perception under terrestrial and microgravity conditions - a conceptual model. *Brain Research Reviews, 28*, 118-135.

Miyasike-daSilva, V., Allard, F., & McIlroy, W. (2011). Where do we look when we walk on stairs? gaze behaviour on stairs, transitions, and handrails. *Experimental Brain Research, 209*, 73-83.

Nougier, V., Bard, C., Fleury, M., & Teasdale, N. (1997). Contribution of central and peripheral vision to the regulation of stance. *Gait & Posture, 5*), 34-41.

Paillard, J. (1996). Fast and slow feedback loops for the visual correction of spatial errors in a pointing task: A reappraisal. *Canadian Journal of Physiology and Pharmacology, 74*, 401-417.

Patla, A. E. (2003). Strategies for dynamic stability during adaptive human locomotion. *Engineering in Medicine and Biology Magazine, IEEE, 22*, 48-52.

Patla, A. E., & Vickers, J. N. (1997). Where and when do we look as we approach and step over an obstacle in the travel path? *Neuroreport, 8*, 3661-3665.

Piponnier, J., Hanssens, J., & Faubert, J. (2009). Effect of visual field locus and oscillation frequencies on posture control in an ecological environment. *Journal of Vision, 9*: 13, 1-10

Prado, J., Clavagnier, S., Otzenberger, H., Scheiber, C., Kennedy, H., & Perenin, M. (2005). Two cortical systems for reaching in central and peripheral vision. *Neuron, 48*, 849-858.

Ricker, K. L., Elliott, D., Lyons, J., Gauldie, D., Chua, R., & Byblow, W. (1999). The utilization of visual information in the control of rapid sequential aiming movements. *Acta Psychologica, 103*, 103-123.

Scalf, P. E., Colcombe, S. J., McCarley, J. S., Erickson, K. I., Alvarado, M., Kim, J. S., et al. (2007). The neural correlates of an expanded functional field of view. *Journals of Gerontology - Series B Psychological Sciences and Social Sciences, 62*, 32-44.

Schlicht, E. J., & Schrater, P. R. (2007). Effects of visual uncertainty on grasping movements. *Experimental Brain Research, 182*, 47-57.

Scovil, C. Y., Zettel, J. L., & Maki, B. E. (2008). Stepping to recover balance in complex environments: Is online visual control of the foot motion necessary or sufficient? *Neuroscience Letters, 445*, 108-112.

Sengpiel, F., & Hubener, M. (1999). Visual attention: Spotlight on the primary visual cortex. *Current Biology, 9*, R318-R321.

Sibley, K. M., Mochizuki, G., & McIlroy, W. E. (2009). Perturbation-evoked electrodermal activity responds to instability, not just motor or sensory drives. *Clinical Neurophysiology, 120*, 619-625.

Singhal, A., Culham, J. C., Chinellato, E., & Goodale, M. A. (2007). Dual-task interference is greater in delayed grasping than in visually guided grasping. *Journal of Vision, 7*: 5, 1-12

Sivak, B., & MacKenzie, C. L. (1990). Integration of visual information and motor output in reaching and grasping: The contributions of peripheral and central vision. *Neuropsychologia, 28*, 1095-1116.

Smith, D. M., & Mizumori, S. J. Y. (2006). Hippocampal place cells, context, and episodic memory. *Hippocampus, 16*, 716-729.

Sung, C., & Chuang, J. (2010). The cell biology of vision. *The Journal of Cell Biology, 190*, 953-963.

Thompson, A. A., & Henriques, D. Y. P. (2011). The coding and updating of visuospatial memory for goal-directed reaching and pointing. *Vision Research, 51*, 819-826.

Tovee, M., J. (1996). *An introduction to the visual system*. Cambridge, UK: Cambridge University Press.

Tripp, B. P., McIlroy, W. E., & Maki, B. E. (2004). Online mutability of step direction during rapid stepping reactions evoked by postural perturbation. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on, 12*, 140-152.

Turano, K. A., Yu, D., Hao, L., & Hicks, J. C. (2005). Optic-flow and egocentric-direction strategies in walking: Central vs peripheral visual field. *Vision Research, 45*, 3117-3132.

Wade, M. G., & Jones, G. (1997). The role of vision and spatial orientation in the maintenance of posture. *Physical Therapy, 77*, 619-628.

Wandell, B. A., Dumoulin, S. O., & Brewer, A. A. (2007). Visual field maps in human cortex. *Neuron, 56*, 366-383.

Westwood, D. A., Heath, M., & Roy, E. A. (2003). No evidence for accurate visuomotor memory: Systematic and variable error in memory-guided reaching. *Journal of Motor Behavior, 35*, 127-133.

Wurtz, R. H. (2008). Neuronal mechanisms of visual stability. *Vision Research, 48*, 2070-2089.

Zettel, J. L., McIlroy, W. E., & Maki, B. E. (2008). Gaze behavior of older adults during rapid balance-recovery reactions. *Journal of Gerontology: Medical Sciences, 63*, 885-891.

Zettel, J. L., Scovil, C. Y., McIlroy, W. E., & Maki, B. E. (2007). Gaze behavior governing

    balance recovery in an unfamiliar and complex environment. *Neuroscience Letters, 422*,

    207-212.

Zettel, J. L., Holbeche, A., McIlroy, W. E., & Maki, B. E. (2005). Redirection of gaze and

    switching of attention during rapid stepping reactions evoked by unpredictable postural

    perturbation. *Experimental Brain Research, 165*, 392-401.