Contributions of Central and Peripheral Vision to the Control of Reach-to-Grasp Reactions Evoked by Unpredictable Balance Perturbation

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Institute of Biomaterials and Biomedical Engineering
University of Toronto

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2009

Abstract

This thesis presents two studies that investigate how vision is used to control rapid, compensatory reach-to-grasp reactions. Compensatory grasping reactions were evoked in healthy young adults via unpredictable translations of large platforms on which the subjects stood or walked. The first study tracked natural gaze behaviour during responses to unexpected balance perturbations. It provided evidence that, unlike with voluntary movements, the eyes do not lead the hand during balance recovery – subjects relied on ‘stored’ information from central vision, continuously-available peripheral vision, or a combination of these sources to guide the hand. The second study investigated the efficacy of reliance on peripheral vision to guide rapid reach-to-grasp balance-recovery reactions. Peripheral vision was found to guide reach-to-grasp responses with sufficient accuracy to achieve a functional grasp of a relatively small handhold; however, peripherally-guided movements were slower when the handhold was in the extreme periphery.
Acknowledgments

I would like to begin by expressing my appreciation to supervisor, Brian Maki, both for introducing me to this field and for the guidance and opportunities he has offered throughout my Master’s work. I would also like to thank the other members of my advisory committee, Tom Chau and Jay Pratt, for their advice and support.

I gratefully acknowledge the funding provided by the Canadian Institutes of Health Research, the Toronto Rehabilitation Institute, the Vision Sciences Research Program and the University of Toronto. I would also like to thank all of the volunteers who participated in my experiments.

My work would have been much more difficult, of poorer quality and no fun at all without the help and the companionship of my colleagues at the Centre for Studies in Aging, from both the balance and technology teams. Thank you all for everything. Special thanks are due to those who helped me to design, prepare, run and analyse my experiments: Carol Scovil, Amy Peters, Sandra McKay, Aaron Marquis, Avril Mansfield, Tracy Lee, Kenneth Cheng and Areeba Adnan have all been a tremendous help.

Finally, I would like to thank my friends and family for their support and encouragement. I dedicate this thesis to my parents, brother and husband in thanks for all of their love, support, advice and patience.
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List of Abbreviations

APA  Anticipatory Postural Adjustment
APR  Automatic Postural Response
BOS  Base of Support
CNS  Central Nervous System
COM  Centre of Mass
FOV  Field of View
VSI  Visual-spatial Information
List of articles arising from this work

King EC, Lee TA, McKay SM, Scovil CY, Peters AL, Pratt J, Maki BE. Reach-to-grasp reactions evoked by unexpected balance perturbation: An exception to the “eyes lead the hand” principle. [in preparation] (Chapter 3)

Scovil CY, King EC, Maki BE. Determining the scene within specified visual angles: An extended application of eye tracker gaze data. IEEE Transactions on Biomedical Engineering. Accepted August 2008. (Appendix)

The method described in this publication was developed to facilitate the analyses required for the experiment which is described in Chapter 3.

Lee TA, Scovil CY, McKay SM, Peters AL, King EC, Maki BE. Age-related differences in reach-to-grasp reactions and associated gaze behaviour evoked by unexpected perturbation when walking in an unfamiliar environment. [in preparation]

The protocol, methods and analysis tools used for the experiment described in Chapter 3 were also applied to this experiment, which investigates the natural gaze and handrail-use patterns adopted by older adults when their balance is perturbed while they are walking through an unfamiliar environment.


This publication introduces the moving handhold apparatus used in the experiment described in Chapter 4.

King EC, McKay SM, Cheng KC, Maki BE. Can peripheral vision of a handhold guide compensatory grasping reactions? [in preparation] (Chapter 4)
Chapter 1
Introduction

1.1 Motivation

Falls and their consequences are a leading cause of injury, nursing home admission and loss of independence for older adults, as well as a common cause of death (Masud and Morris 2001). With the aging of the baby boom, the proportion of Canadians over 65 will nearly double by 2031 (StatisticsCanada 2005). With a larger population of older adults facing age-related increases in the risk of falling, it is becoming increasingly urgent that we understand the causes underlying falls, especially those associated with aging. An improved understanding of these causes will enable the development of better tools for identifying those who may be at risk, as well as more effective interventions to help seniors to avoid falls, thus reducing healthcare costs while allowing people to maintain their independence and quality of life as they age.

In essence, a fall is the result of a loss of balance followed by a failure to recover. The loss of balance is most commonly caused by an external perturbation, either physical or informational in nature (Maki and McIlroy 1996). Given that it almost impossible to avoid all forms of postural perturbation in daily life, a critical factor in fall aversion is the ability to recover balance. Change-in-support reactions, in which a step is taken or a part of the environment is grasped for support, provide a critical defence against falling (Maki and McIlroy 1997). These rapidly initiated limb movements are the only effective response to large postural disturbances (Shumway-Cook and Woolacott 1995), but are also often the preferred response to smaller postural perturbations (Maki and Whitelaw 1993; McIlroy and Maki 1993c; Maki and McIlroy 1997; Jensen et al. 2001). For change-in-support reactions to arrest falls effectively they must be initiated rapidly, land on a stable target location and allow a moment to be generated which will counter the motion of the centre of mass.

In recent years it has become clear that the arms play an active role in postural control and in the restoration of balance. Indeed, studies of video-recorded loss-of-balance events in natural environments have shown that compensatory arm reactions occur as part of the balancing responses used in 65-75% of falls and near-falls (Maki and McIlroy 1996; Maki and McIlroy
Similar results have been found experimentally: McIlroy and colleagues found a very high prevalence of arm reactions (85% of trials) when they instructed standing subjects to respond naturally to postural perturbations delivered by sudden support-surface translation (McIlroy and Maki 1995b; Maki and McIlroy 1997). In an experiment using a sudden, unexpected slip during normal walking to perturb balance, Marigold and colleagues have also found that the majority of participants included a rapid arm elevation in their balancing strategy, especially on the first exposure to the perturbation (Marigold et al. 2003).

There are a variety of ways in which arm reactions can contribute to balance recovery: in some cases, they serve a protective role, absorbing some of the energy from the initial impact of a fall (Chiu and Robinovitch 1998; Hsiao and Robinovitch 1998); however, they can also be used to prevent falls, providing stabilization through inertial effects or grasping some feature of the environment for support (McIlroy and Maki 1995b; Maki and McIlroy 1997). The study by McIlroy and colleagues, referred to above, found a preference for the use of a handrail to restore balance when one was available. When the handrail was within easy reach, subjects made contact with it in 78% of trials. When the handrail was far enough away that the subject would also have to step to reach it, the handrail was still contacted in 3% of trials. In many trials of both types, the hand reached toward the handrail but stopped short of making contact with it. These reactions were interpreted by the authors as aborted grasping responses (McIlroy and Maki 1995b). This preference for the use of a handrail likely stems from the increased stability that can be gained by the use of this change-in-support response.

1.2 Thesis Objectives

Given the prevalence and functional importance of reach-to-grasp balance recovery responses, an improved understanding of how these responses are controlled will be of use in understanding the factors which affect the risk of falling and potentially in the development of improved fall-prevention strategies. To direct limb motion towards an appropriate target, the control of reach-to-grasp reactions is highly dependant on vision to provide information about the location and characteristics of the handhold. It is not currently clear exactly when and how this visual spatial information is obtained. Two areas of uncertainty are when this information is obtained and what areas of the visual field are required to obtain it. The issue of visual control of movement has been studied extensively for voluntary actions and has also been addressed to
some extent with regard to compensatory stepping reactions. However, it remains unclear as to how well these results will generalize to compensatory grasping behaviour, given the heightened temporal demands presented by a loss-of-balance situation.

The work presented herein aims to identify and evaluate the visual strategies used by young adults to control compensatory reach-to-grasp reactions. Specifically, this thesis presents two studies. The first study, presented in Chapter 3, examines the relationship between gaze behaviour and handrail use when balance is recovered in response to an unexpected perturbation experienced while walking in a complex environment of the type generally encountered in daily life. The gaze behaviours identified in this experiment provide insight into how the visual-spatial information used to guide compensatory reach-to-grasp reactions is gathered under natural circumstances, and thus indicate which information-gathering patterns would be most useful to investigate in future studies. The second experiment, described in Chapter 4, is the first of a planned series of detailed experiments investigating the efficacy of the information-gathering strategies identified in Chapter 3 for guiding successful compensatory reach-to-grasp reactions. Specifically, this second experiment investigates the efficacy with which reach-to-grasp reactions guided using only peripheral vision are controlled. In addition, the effects of an ongoing cognitive task on the efficacy of the peripheral-vision guided response are investigated. The findings of these experiments will serve as a baseline for comparison with the prevalence and efficacy of visual strategies used by older adults to guide balance recovery, allowing age-related changes in the visual control of reach-to-grasp reactions to be identified.

1.3 Contributions

The experiment described in Chapter 3, “Reach-to-grasp reactions evoked by unexpected balance perturbation: An exception to the “eyes lead the hands” principle”, was planned by other researchers prior to the beginning of my graduate work. I participated in data collection, performed the majority of data processing, conducted all data analysis, and prepared the manuscript describing this experiment. I also co-developed a new analysis tool used to determine the visual angles to features of interest in the environment. The publication describing this work is reproduced in the Appendix (Scovil et al. 2008a). The protocol and analysis procedures for this study are also used in a study which investigates the natural gaze and
handrail-use patterns adopted by older adults when perturbed while walking through an unfamiliar environment (Lee et al. in preparation).

For the experiment described in Chapter 4, “How well can peripheral vision of a handhold guide compensatory grasping reactions?”, a generalized protocol to be used for a series of similar studies was developed, under Dr. Brian Maki’s direction, through an equal collaboration between Kenneth Cheng, Dr. Sandra McKay and me. The equipment and general protocol are described in “The Moveable Handhold: A new paradigm to study visual contributions to the control of balance-recovery reactions” (Cheng et al. 2008). I adapted this general protocol for use in the study described in Chapter 4, led all data collections, analyzed the data and prepared the manuscript. Kenneth Cheng provided substantial assistance with the statistical analysis.
2.1 An Introduction to the Maintenance of Postural Balance

The maintenance of postural balance is a complex task, requiring the central nervous system (CNS) to integrate multi-modal sensory inputs (somatosensory, visual and vestibular) to monitor the stability of the body’s centre-of-mass (COM) relative to the base of support (BOS), and to determine and execute appropriate muscular responses to counter any undesirable motion of the COM (Maki and McIlroy 2007) while still allowing useful COM motion, as in walking. A consequence of the inherent biomechanical instability of the human body is that the maintenance of postural balance requires continual monitoring and adjustments to the movement of the COM through the deceleration of ongoing motion and to the size, shape and location of the BOS (Maki and McIlroy 1996; Maki and McIlroy 1997; Maki et al. 2003).

When postural balance is perturbed, a fall can be avoided if the CNS acts quickly to ensure that the COM remains within the BOS. This can be achieved through modifications to the movement of the COM and/or through changes to the BOS. The majority of early balance research focused on fixed support (FS) reactions, in which ongoing motion of the COM is decelerated without changes to the BOS (e.g. Nashner 1976; Nashner 1977). FS reactions generally involve the generation of stabilizing torques at the ankles and/or the hips, and can also involve other contortions of the torso and arms to aid in countering ongoing motion of the COM through inertial effects (Moore et al. 1988; Shumway-Cook and Woolacott 1995; Henry et al. 1998a; Henry et al. 1998b). These FS reactions are sufficient to respond to comparatively small perturbations of the COM; however, they can not provide sufficient stabilization to counter large-magnitude perturbations (Shumway-Cook and Woolacott 1995). In these cases it is also necessary to increase the BOS, usually by taking a step or by grasping an object in the environment for support (Maki et al. 2003). This strategy provides for greater stability both by increasing the range of ‘stable’ COM displacement and by increasing the moment arm between the COM and the point of force application. These responses have been termed change-in-support (CIS) reactions and are the only feasible response to large-magnitude perturbations
(McIlroy and Maki 1993c; Maki and McIlroy 1997). However, it has also been found that these reactions are often the preferred response even to lower-magnitude perturbations, when it would also be sufficient to respond with a FS reaction (Maki and Whitelaw 1993; McIlroy and Maki 1993c; Maki and McIlroy 1997; Jensen et al. 2001).

### 2.2 Characteristics of Change-In-Support Reactions

The majority of existing balance research has focused on the lower limbs, and studies of change-in-support reactions are no exception. Only recently have researchers started to appreciate and study the roles of the arms in balance control, both in FS reactions through inertial effects and in CIS reactions through contact with stable features of the environment such as walls and handrails (McIlroy and Maki 1995b; Tang et al. 1998; Marigold et al. 2003). As a result, there is little existing literature describing reach-to-grasp balance recovery reactions; however, because there are thought to be similarities in the control of CIS responses of the upper and lower limbs, a general understanding of compensatory stepping responses can serve as a guide to what may be seen in compensatory reaching.

#### 2.2.1 General Features of Change-In-Support Reactions

Arguably the most interesting feature of a CIS reaction is the rapidity with which it is initiated. Both compensatory steps and reach-to-grasps are initiated about 100 ms earlier than the corresponding voluntary movements, even when subjects are instructed to react as quickly as possible to a visual or auditory cue (McIlroy and Maki 1996; Luchies et al. 1999; Gage et al. 2007). Compensatory steps are also consistently executed more rapidly than voluntary steps, being completed in about half of the time of a corresponding voluntary step, even when the subject is instructed to step as quickly as possible (McIlroy and Maki 1996; Luchies et al. 1999; Maki et al. 2003).

CIS responses of both the upper and lower limb are accompanied by an early activation of the ankle musculature, often referred to as the automatic postural reaction (APR) (Nashner 1977; Maki and McIlroy 2007). Both in terms of latency (80-140 ms) and in the muscles activated (flexors and extensors of the ankle), this early response is very similar to the fixed-support ankle strategy mentioned above, with the important difference that it forms only one part of the balance recovery reaction (Maki et al. 2003). This APR acts to provide some initial
stabilization, reducing the velocity of the COM and allowing more time for subsequent phases of the balance recovery response to be planned and executed. The APR is referred to as automatic because, while its timing and magnitude are scalable, it is always present, regardless of the task constraints, perturbation magnitude, or effect of repeated perturbations.

A compensatory step begins, on average, 230 ms after the perturbation onset - approximately 100 ms faster than a voluntary step can be initiated (McIlroy and Maki 1996). In voluntary stepping, even when subjects are asked to step as rapidly as possible, the first biomechanical sign of step initiation is an ‘anticipatory postural adjustment’ (APA) before foot-off, in which the COM is shifted toward the stance leg to ensure that it is adequately supported during the step (McIlroy and Maki 1996). In compensatory stepping, the APA tends to be either smaller than usual or entirely absent, especially when pre-planning of the step has not occurred (McIlroy and Maki 1993b). This shortening or elimination of the APA allows the step to be initiated more quickly, although lateral stability is reduced. It should be noted that while an APR is unaffected by an ongoing cognitive task, such a task can affect the CIS part of the balance recovery response, delaying the initiation of the APA and of foot-off (Maki and McIlroy 2007).

2.2.2 Characteristics of a Compensatory Reach-to-Grasp

In compensatory arm reactions, unlike compensatory stepping responses, there is no need to sacrifice stability for speed when initiating the response, because the upper limbs are not typically supporting any bodyweight. In fact, CIS responses of the arms can be initiated in parallel with the APR; deltoid activation can occur as soon as 90 ms following the perturbation (McIlroy and Maki 1995b). Reach-to-grasp responses can thus be initiated very rapidly.

It is primarily in this rapidity that the mechanics of compensatory reaching differ from those of voluntarily-initiated reaching. The fastest volitional reaches can be initiated approximately 240 ms after the onset of an auditory cue (Gage et al. 2007), but compensatory arm reactions are initiated within 80-140 ms of the onset of a balance perturbation, over 100 ms earlier (McIlroy and Maki 1995b; Maki and McIlroy 1997; Ghafari et al. 2004; Gage et al. 2007; Mansfield and Maki submitted). Movement times are also faster and less variable for perturbation-evoked reaching movements than their voluntarily-initiated counterparts (Maki and McIlroy 1997; Gage et al. 2007), and peak wrist velocities were higher for the perturbation-evoked reach-to-grasps (Gage et al. 2007). Despite these differences, perturbation-evoked
reaches resemble rapid reaction-time voluntary reaches in most respects. Gage and colleagues have found that the overall movement profiles between these types of reaches are quite similar: the sequencing of muscle activations for movement initiation were all similar, as were the relative timings of peak wrist velocity and peak grasp aperture (as fractions of total movement time) and the presence of muscle activity in the triceps, deltoid and forearm flexors just prior to contact, suggesting that the CNS is anticipating the contact time and preparing to use the arm to stabilize the body (Gage et al. 2007).

2.3 Visual Control of Compensatory Reach-to-Grasp Reactions

In addition to the biomechanical requirements of the successful execution of a compensatory grasp, there are the added complications of locating an appropriate handhold in the environment, directing the hand toward that handhold while compensating for ongoing shoulder movement caused by the balance perturbation, positioning the hand appropriately based on the characteristics of the target handhold and timing all of the above to ensure that the hand and arm are ready at the time of contact with the handrail (Maki and McIlroy 1997). It is remarkable that despite the extent of these task requirements, the reaction is generally executed successfully, even in response to an unfamiliar balance perturbation (Maki and McIlroy 1997). Because the only source of information about the handhold location and characteristics available prior to contact with the handrail is vision, an understanding of how the visual system acquires this information would provide valuable insights into how these reactions are controlled. To date, little research has been conducted regarding how visual-spatial information (VSI) for these reactions is acquired and used.

2.3.1 When is visual-spatial information acquired?

It has been proposed that the CNS automatically maintains and updates an egocentric visual-spatial map of salient features of the environment, such as potential obstacles or handholds. In the event of an unexpected loss of balance this preformed map can be used, in combination with online somatosensory and vestibular feedback, to allow the rapid initiation of appropriately-directed balance recovery responses (Ghafouri et al. 2004; Zettel et al. 2005). This
strategy has the advantage of avoiding delays associated with waiting for online visual-spatial information to be gathered and processed.

There is now substantial evidence that stored-VSI is indeed the preferred source of information for guiding the early phases of CIS reactions. Early studies of compensatory stepping showed that in comparatively simple recovery situations (i.e. no particular constraints on foot trajectory or landing target), stored-VSI is sufficient to guide stepping and is likely the preferred strategy (Zettel et al. 2005). To further test the capacity of subjects to respond using only stored-VSI, Scovil and colleagues deprived subjects of all vision after perturbation onset as they stepped through a small slot over a challenging obstacle. In this study, movement accuracy, step timings and foot trajectory were the same when only stored-VSI was available as when full vision was used. However, when the subjects were forced to rely on online vision, marked differences in strategy (the use of a small preliminary step, and/or ‘incorrect’ foot selection for the step), increased frequency of barrier contact, and delayed foot-off were observed (Scovil et al. 2008b). There is also evidence which points to a preference for using stored-VSI to guide at least the early phases of a compensatory reach trajectory. Ghafouri and colleagues found that the first 100ms of a perturbation-evoked reach’s trajectory were appropriately-directed to accommodate both handhold location and ongoing motion of the body, even when vision was occluded following perturbation onset (Ghafouri et al. 2004). An unpublished study by McIlroy and colleagues found that unpredictable variation in handhold location prior to the onset of perturbation leads to a loss of this ability to appropriately direct the initial reach trajectory, although it does not delay response initiation (Maki and McIlroy 1997). Thus for CIS responses executed with either the upper or lower limbs, it is clear that the use of stored-VSI allows accurate planning and, for stepping responses, allows faster response initiation than when online-VSI is used.

While the early phases of a trajectory may be based on pre-stored visual information, the visual requirements for completing the final phases of the reaction may be significant. In the compensatory stepping studies noted above (Zettel et al. 2005; Scovil et al. 2008b), the step ‘target’ (i.e. the floor) was large and predictably located. Further studies by Zettel and colleagues found that when both an obstacle and target landing site constrained stepping, subjects saccaded downwards, away from an ongoing tracking task, in 37% of trials (Zettel et al. 2005). When a more complex obstacle setup was used in the absence of either a step target or a
secondary task, 90% of subjects saccaded downwards, to a point anterior to the eventual foot placement during their balance recovery (Zettel et al. 2007). In both of these cases, the presence of downward saccades during balance recovery can be interpreted as attempts to gain online-VSI to guide the later phases of the step. While this may not have been absolutely necessary, given the success of Scovil’s subjects in obstacle avoidance with no online-VSI (Scovil et al. 2008b), it seems that the preference is still to have online-VSI during the later phases of a stepping response. No analogous studies have yet been performed for compensatory reach-to-grasp responses. However, given that the target of a grasping reaction (e.g. a handrail) tends to be smaller and less predictably-located than the target of a stepping reaction, it seems reasonable to expect that online-VSI may play a more important role in guiding the later phases of grasping reactions.

2.3.2 What areas of the visual field are used to guide CIS reactions?

To date, this question has not been a focus of research into compensatory grasping; however, research which has focused on what areas of the visual field are used to guide compensatory stepping and adaptive locomotion may provide some indication as to how balancing reactions involving a CIS are controlled in general.

In general, studies of gaze behaviour during adaptive locomotion have shown that the planning of gait modifications is carried out in a feed-forward manner and fixation of an obstacle or step target typically occurs between one (Hollands et al. 1995; Hollands and Marple-Horvat 2001) and two (Patla 1997; Patla and Vickers 1997; Land 2006; Marigold and Patla 2007) steps ahead of obstacle crossing or foot placement. Gaze is not directed at an obstacle during the actual step over it (Patla 1997). Marigold and colleagues found that even when an obstacle appears suddenly in the travel path, less than one step ahead, it is rare for gaze to be directed toward it. In the 18% of trials in which downward gaze shifts were made, they were directed to a point near the landing site, rather than toward the obstacle (Marigold et al. 2007). This redirection of gaze is similar to the gaze shifts observed during compensatory stepping reactions to a point anterior to the landing site (Zettel et al. 2007). However, there is growing evidence that while fixation of an obstacle in the travel path during obstacle crossing is not necessary, visual feedback is still desirable. When no online vision of the obstacle and lower limbs is available during obstacle crossing, lead and trail foot distances to the obstacle, toe clearances and
lead-foot step length all increase (Rietdyk and Rhea 2006). The provision of obstacle position cues can compensate for errors in foot placement (Rietdyk and Rhea 2006), but indirect obstacle height cues available from objects placed alongside the subject’s path do not alter the toe clearance or variability, compared to when this information is unavailable (Rhea and Rietdyk 2007). Given that gaze shifts would not normally be expected during obstacle crossing, these changes when no online vision of an obstacle is available suggest that online peripheral vision normally plays an important role in guiding obstacle avoidance. Similar support for the importance of peripheral vision in navigating multi-surfaced terrain has been found by Marigold and colleagues, who found that, when deprived of lower peripheral vision, subjects tended to increase their downward head pitch to compensate (Marigold and Patla 2008). There is even some evidence that the use of peripheral vision alone may be the preferred strategy for some situations (Marigold et al. 2007).

2.3.3 How is vision used to guide grasping?

While there may prove to be some similarities in the visual control of stepping and grasping change-in-support reactions, the visual demands of grasping are greater than those of stepping. This is primarily because the target of stepping is almost always the floor, which tends to be in a predictable location. As noted above, the target of a grasping reaction (e.g. a handrail) tends to be smaller and less predictably located than the target of a stepping reaction. Thus, to guide a grasping reaction, vision must provide much more detail regarding the location and characteristics of the target. A greater understanding of how this can be done may be gleaned from an examination of the substantial body of work which has focused on understanding the visual control of volitional arm and hand movements.

2.3.3.1 Natural Hand-Eye Coordination

Typically, the visual control of upper limb movements in daily life involves a tight coupling between gaze direction and the target of the aiming, pointing, reaching or grasping motion (Desmurget et al. 1998; Henderson 2003; Hayhoe and Ballard 2005; Land 2006). In complex activities of daily living, such as making tea or sandwiches, the eyes tend to fixate on an object around half a second before the hands reach toward it, with these saccades often being initiated before the hands have finished with the previous task (Land 2006). A similar correlation has been shown in laboratory experiments in which the subject is not given explicit
instructions regarding where to look while performing a manual task (Prablanc et al. 1979; Abrams 1992; Sivak and MacKenzie 1992), with saccades arriving at the target location approximately 200 ms before the end of the hand movement (Abrams 1992). Remarkably, this saccade pattern persists even in the absence of any retinal feedback (i.e. when no light is available in the environment following task initiation) (Abrams 1992). This implies an attempt to use the additional information obtained from ‘extraretinal’ sources: the efference copies of motor commands to the extraocular muscles and the proprioceptive (afferent) feedback from these muscles affects where the CNS determines that the things we see are located in our environment. Desmurget and colleagues have reviewed how retinal and extraretinal information sources interact to allow accurate target localization. They found that when only extraretinal information is available, pointing variability is high, indicating that direction is only coarsely encoded. However, a variety of studies in both humans and monkeys in which extraretinal information has been modified have found that manual responses will tend to point in the direction indicated by the faulty extraretinal information. Desmurget and colleagues conclude that while extraretinal information alone provides a crude estimate of target position, it interacts synergistically with visual information to provide a more accurate position estimate (Desmurget et al. 1998). More recently, Lewald and colleagues have found that when a subject fixates on and points to a target in the periphery, the response tends to undershoot the target by approximately 0.12° per degree of target eccentricity, and that this effect is additive with any offsets due to the retinal eccentricity of a target (Lewald and Ehrenstein 2000).

2.3.3.2 Control of Reaching using Peripheral Vision

Aiming, pointing and reaching movements guided only by peripheral vision have been studied extensively, but generally under fairly constrained circumstances. The simplest of these experiments have examined one-dimensional pointing movements. The basic format of these studies is that the subject sits in a barren, usually dark environment and fixates on a central target positioned at eye level at the subject midline. A peripheral target appears and the subject points toward this target, providing an estimation of eccentricity (typically azimuth angle). There have been a wide variety of methodological variations in these studies, affecting whether or not visual feedback of hand position is available before and/or during the movement; whether the target and fixation point remain visible throughout the movement or are extinguished at onset; whether the environment is dark or light, unstructured or visually rich; how exactly the subject points to the
target (manipulandum, stylus, finger, the degrees of freedom of the movement, etc); and the range of angular eccentricities studied. Each of these factors affects the experimental outcome to some degree; however, despite these differences, a consistent finding has been that subjects tend to overshoot when pointing to a target in the visual periphery (Bock 1986; Bock 1993; Henriques et al. 1998; Lewald and Ehrenstein 2000; Henriques and Crawford 2002). Studies which have quantified the degree of overshoot for azimuth angles ranging from 5-30° have found this bias to be of a consistent magnitude regardless of angular eccentricity, and to be in the range of 2.6° (Lewald and Ehrenstein 2000) to 3.8° (Bock 1986). Bock also looked at the estimation of direction along the vertical axis. He found that the accuracy of elevation angle estimates showed a similar pattern to the estimation of azimuth angle estimates for the range he investigated (1-10°) (Bock 1993). A further consistent finding in these studies is that the endpoint variability of the pointing movements is greater when pointing movements are made without foveal vision of the target (Bock 1986; Blouin et al. 1996; Henriques et al. 1998; Ma-Wyatt and McKee 2006). Some studies have found variability to be eccentricity-dependent (Ma-Wyatt and McKee 2006; Schlicht and Schrater 2007) while others have found no evidence of this (Bock 1986). Despite this difference, these studies did still agree on the fundamental point that positional variability is greater when pointing to targets using peripheral rather than central vision. The general consensus among the above studies is clear: in pointing to targets in the visual periphery, subjects will tend to overestimate angular eccentricity, and their responses will be more variable than if they are permitted to saccade to the target before pointing.

The accuracy of movement depth in reaching to peripheral targets has received less attention. In one study which did focus on depth accuracy of pointing movements in the periphery, Bock found that subjects’ estimations of absolute depth were poor, but that their estimations of the relative depths of two targets seen only in the periphery were quite accurate. Furthermore, these estimates of relative depths were not significantly different than those found when subjects foveated on the peripheral targets (Bock 1993).

Further evidence for the accuracy and precision of depth estimation in the peripheral visual field comes from studies in which subjects were required to reach to grasp a small object (Sivak and MacKenzie 1990; Schlicht and Schrater 2007). These studies have, on examining the wrist kinematics, found that the wrist slows earlier when the reach is carried out in peripheral vision than when it is carried out in central vision. Sivak and MacKenzie interpreted this finding
as a greater tendency to underestimate the target distance when the reach is in peripheral vision (Sivak and MacKenzie 1990; Sivak and MacKenzie 1992); however, an alternative explanation is that this is merely a reflection of a conservative strategy used to avoid collisions with the target despite increased uncertainty regarding the target distance when the object is peripheral vision (Schlicht and Schrater 2007).

With respect to the accuracy of grasping in the peripheral visual field, studies to date have focused primarily on ‘precision grasps’ of comparatively small objects (cylinders or rectangular prisms) made with the thumb and index finger. They have found that the maximum grip aperture between the thumb and index finger during the reach toward the object is consistently greater when only peripheral vision is used than when the eyes are allowed to lead the hand (Sivak and MacKenzie 1990; Brown et al. 2005; Schlicht and Schrater 2007). The degree of this overestimation increases linearly with increased target eccentricity, despite the relative positions between the subject’s body and the target remaining constant (Goodale and Murphy 1997; Brown et al. 2005; Schlicht and Schrater 2007). While this may be attributed to increased uncertainty about the target width, it is interesting to note that the variability in maximum aperture did not scale with eccentricity (Goodale and Murphy 1997; Brown et al. 2005), perhaps implying that this tactic is being used to compensate for increased directional uncertainty, rather than uncertainty about the target size.

There are a couple of important environmental considerations which can have substantial effects on the accuracy and precision with which peripheral vision is able to guide pointing, reaching and grasping movements:

1. The degree of structure in the environment is a factor which has been shown to affect pointing accuracy substantially. Many studies of aiming, pointing or reaching to peripheral targets are conducted in an environment in which the visual scene is entirely devoid of structure, often dark, and in which the only visual stimuli come from small lights indicating fixation point, target position, and sometimes finger position. These basic testing environments allow clear conclusions to be drawn about the relative contributions of retinal and extraretinal inputs to the control of pointing under various conditions; however, they do not allow the CNS to use its full set of tools for determining target locations. A variety of recent studies have demonstrated that the availability of even a very minimal amount of structure in the visual scene improves the
accuracy of reaching to targets in the visual periphery, both in terms of azimuth angle (Blouin et al. 2002; Priout et al. 2002) and depth (i.e. distance anterior to the subject) (Coello and Magne 2000; Magne and Coello 2002).

2. Movement accuracy and variability is also affected by whether or not subjects have any visual feedback regarding arm and/or hand position during the movement. Unsurprisingly, both the accuracy and precision of these movements are improved when online visual feedback of hand position is available, independent of whether or not a saccade to the target is made (Prablanc et al. 1979; Sivak and MacKenzie 1992; Paillard 1996). A variety of studies have also been directed at discovering when visual feedback regarding hand position is useful and how it affects reaching motions. Even if the hand is fixated before starting the movement (but no online feedback is available during movement), accuracy improves (Sivak and MacKenzie 1992; Bédard and Proteau 2001). Still greater improvements are found when online feedback is available even in the early phases of a movement in peripheral vision, as is common in most natural reaching movements (Sivak and MacKenzie 1992; Blouin et al. 1993; Proteau and Marteniuk 1993; Bédard and Proteau 2001; Khan et al. 2004), with the majority of the benefit coming from improved directional accuracy, rather than any improvements in the accuracy of movement extent (Bédard and Proteau 2001). A central issue to the role which can be played by online visual feedback is how long it takes to incorporate this information to correct ongoing actions. For many years, the standard benchmark processing time was considered to be in the range of 190-260 ms, as established by Keele & Posner in 1968. Some authors have since presented evidence of faster visually-triggered corrections, with latency as low as 100 ms, but these findings have not been consistent, implying a substantial dependency on experimental conditions (for a review, see: Paillard 1996).

2.3.3.3 Control of Reaching in the Absence of Peripheral Vision

Another approach to understanding the role of peripheral vision in guiding reaching movements is to occlude it, forcing subjects to rely on central vision alone. A number of experiments have used this approach, limiting the field of view (FOV) by using blinders or ‘pinhole’ goggles. With this restricted vision, the subject is required to reach to grasp small cylinders or rectangular objects using a ‘precision grip’ with the thumb and index finger. The
primary findings of these studies have been very consistent, despite some methodological variations.

As is common in reaching tasks performed under full vision conditions, subjects tend to undershoot the required reach distance when their peripheral vision is limited (Sivak and MacKenzie 1990; Coello and Grealy 1997; Watt et al. 2000). Interestingly, the magnitude of this undershoot increases as the FOV decreases (Coello and Grealy 1997; Watt et al. 2000). While the undershooting of distance in the above studies can be interpreted as evidence of the perception of shorter distances when peripheral vision is unavailable, it could also represent a cautious strategy used to cope with greater uncertainty in reach distance. In the studies cited above, over-reaching could have resulted in knocking over the reach target, making it more difficult to grip. In contrast, under-reaching merely causes the movement to take a little longer. Decreases in peak wrist velocity during reaching (Watt et al. 2000; Gonzalez-Alvarez et al. 2007) and increased movement time, especially after peak velocity (Sivak and MacKenzie 1990; Watt et al. 2000; Gonzalez-Alvarez et al. 2007), have also been common findings in these studies. This change means that the hand and target are both visible in the central visual field for longer, thus allowing for online corrections based on hand-target position errors detected by central vision. An additional sign of uncertainty regarding target distance is that while deprivation of peripheral vision does not tend to change either the timing (Sivak and MacKenzie 1990) or size (Sivak and MacKenzie 1990; Watt et al. 2000) of the peak grip aperture during a reach, it does affect when subjects close their hand: Sivak and Mackenzie found that with only the central 10° of vision available, subjects often waited for contact with the target object before closing their grip (Sivak and MacKenzie 1990). All of the above findings are consistent with the idea that when the FOV is restricted there is greater uncertainty with regard to the required extent of a reaching movement, leading more cautious strategies to be adopted.

2.4 Conclusions

To date, very little study has been made of the control of the rapid reach-to-grasp reactions to postural perturbations, despite the prevalence and functional importance of these responses for the prevention of falls. Expectations of how these reactions are controlled can be based on two existing bodies of literature: that focusing on voluntary reaching and that focusing on compensatory stepping, the other common form of change-in-support reaction. The control
of compensatory stepping been has found to differ from the control of voluntary stepping in a number of ways: not only are kinematic adjustments made to ensure that the reaction can be initiated and executed very rapidly; but it has been found that saccades are not always made to obstacles to be avoided or to stepping targets during balance-recovery reactions, leaving stored VSI and/or online peripheral vision to guide the reactions. From research into volitional grasping, it is clear that central vision is the preferred source of target information for guiding reaching movements: under natural circumstances, the eyes lead the hand. However, it is possible for reaches to be guided using only peripheral vision of the target location, albeit with less accuracy and precision. Existing studies of reach-to-grasp reactions have indicated that pre-stored VSI is used to guide the first 100 ms of a reach trajectory, but visual control after this point has not yet been studied. The objectives of this thesis are: 1) to investigate which sources of VSI are naturally used to guide compensatory reach-to-grasp reactions executed in response to an unexpected balance perturbation; and 2) to determine how well compensatory reach-to-grasp reactions can be guided using only peripheral vision.
Chapter 3
Reach-to-grasp reactions evoked by unexpected balance perturbation: An exception to the “eyes lead the hand” principle

3.1 Introduction

A fundamental principle that has emerged from studies of natural (unconstrained) gaze behavior is that “the eyes lead the hand” during volitional goal-directed arm movements. This is the case whether the aiming or reaching movement is performed as an isolated task (Abrams 1992) or occurs within the context of a more complex daily-life activity (Land 2006). Typically, a saccade to the target is initiated prior to the start of the limb movement, although the limb may sometimes move first (Abrams 1992). Nonetheless, because the saccade is much faster than the limb movement, visual fixation of the target almost always occurs well before the hand reaches the target (Carnahan and Marteniuk 1991; Abrams 1992). This gaze behavior facilitates control of the limb movement by providing high-acuity retinal information about the location and characteristics of the target, as well as the relative position of hand and target during the final stages of the movement (Abrams 1992). Extra-retinal (oculomotor) information about the eye orientation and saccade amplitude can also contribute to the programming of the limb movement (Enright 1995; van Donkelaar 1998).

The purpose of this research note is to document initial evidence that clearly demonstrates that there is a natural situation in which the “eyes lead hand” principle does not apply, namely, the control of rapid reach-to-grasp balance-recovery reactions evoked by a sudden unexpected balance perturbation. These perturbations involved forward translation of a large motion platform on which the subjects ambulated. To simulate a natural situation, the platform was configured to resemble a visually-complex, “real-life” office environment, and subjects were asked to perform a typical task of daily life that required walking to the end of the platform. The platform translation was triggered to occur as the subject walked alongside a handrail mounted on the platform, and a deception was employed to ensure that the perturbation was truly unexpected. Analysis was restricted to one trial per subject - the subject’s first exposure to the environment and perturbation. Although this single-trial approach severely limits the quantity of data that can be collected, it is essential in order to avoid the adaptations that can
occur when multiple trials are performed and subjects know in advance they may experience a balance perturbation (McIlroy and Maki 1995a; Pavol et al. 2004).

While work aimed at providing detailed characterisation of perturbation-evoked arm reactions is in progress, the initial results presented here provide clear counter-examples that violate the “eyes lead hand” principle. Specifically, it will be shown that all six subjects who grasped or touched the handrail in response to the perturbation initiated the arm movement without first executing a saccade to the rail. Furthermore, two of the six did not look at the rail at any point during the trial, indicating a complete reliance on peripheral vision to locate the rail. A new methodology, developed by the authors (Scoville et al. 2008a), was used in processing the gaze data, in order to quantify the extent to which the rail was visible within the central and peripheral visual fields. To further explore the role of peripheral vision, we also present initial results from a supplementary experiment in which subjects wore goggles that occluded peripheral vision.

3.2 Methods

Participants

Twelve young adults (age 20-30, 6 male) participated in Experiment 1, and ten additional young adults (age 20-30, 5 male) participated in Experiment 2. All participants were naïve to the specific purpose of the study, and had not participated in any previous balance studies. All were right-handed, had a minimum corrected Snellen visual acuity of 20/40, and reported no neurological, sensory or musculoskeletal deficits. Each subject provided written informed consent, in compliance with the ethical approval granted by the institutional ethics review board.

Protocol

A large computer-controlled motor-driven motion platform (2x6m) was set up to simulate a “real-life” office environment, including a stair, handrail, desk and telephone, plus various visual distracters (Figure 3.1a, 3.1b). A wall and door prevented the subject from viewing the environment prior to the start of the trial. A standardized script was read to the subjects immediately prior to starting the trial. This script informed the subjects that there was a room behind the door, with an office area located at the far end of the room, and instructed them to open the door, enter the room, walk to the end at a normal pace and place a telephone call. This
task thus required a visual search for the telephone while walking to the end of the platform. For safety, all subjects wore a harness attached to a low-friction overhead track that moved smoothly and did not impede the subject’s movements.

The handrail and stair were mounted near the middle of the platform, with the near end of the rail located 1.8 m from the door and 1.5 m in front of the stair riser. Sudden forward translation of the platform (square-wave acceleration/deceleration profile: amplitude $3.5 \text{m/s}^2$, peak velocity $1.1 \text{m/s}$, displacement $0.43 \text{m}$, duration $0.6 \text{s}$) was triggered to occur when the subject stepped on a pressure-sensitive mat adjacent to the handrail, thereby inducing a backward falling motion (similar to the effect of a slip). Objects mounted on the platform forced subjects to walk within a relatively narrow corridor (0.74 m wide) when approaching the stair, and thereby ensured that the handrail was well within reach when the perturbation was delivered. The rail was cylindrical, with a diameter (38 mm) and height (0.88 m above the leading edge of the stair) previously shown to allow effective grasping by persons encompassing a wide range of body heights and hand sizes (Maki et al. 2006).

To avoid confounding effects of learning and adaptation, analysis was restricted to one trial per subject, which was the subject’s first exposure to the platform motion and to the simulated office environment. A deception was used to ensure that the perturbation was truly unexpected: subjects were told that the first trial was a “practice trial” to help them become accustomed to the testing procedure and that the platform would not move during this trial.

In Experiment 1, subjects completed the above protocol under “natural” (unrestricted) visual conditions. Experiment 2 required a second cohort of subjects to perform the same protocol while wearing custom-designed goggles that occluded a large portion of the peripheral visual field, i.e. all but the central $15^\circ$ of the visual field (Figure 3.1c). A geometric optical model indicated that the occlusion was accurate to within $\pm 2^\circ$ across subjects, with the variability resulting from differences in goggle-to-eye distance due to variation in facial structures. In both experiments, subjects were given no instructions regarding their gaze behavior.

**Data collection and analysis**

Eye movements and changes in gaze direction were recorded in Experiment 1 using a binocular eye tracker (Model 501, Applied Sciences Laboratories, Bedford, MA). The eye
tracker uses infrared corneal reflections to determine gaze direction, relative to the head, and superimposes the gaze location on 60-Hz video images recorded by a forward-facing “scene camera” mounted rigidly on the head. Custom-designed software was used to augment these point-of-gaze data by superimposing “gaze ellipses” (corresponding to visual angles of 5°, 10°, 15°, 20°, 30° and 40°, in relation to the point of gaze) on each frame of the scene-camera video (Figure 3.1d) (Scovil et al. 2008a). These images were used to determine whether visual fixation of the handrail occurred, as well as the onset time and duration of each such fixation or near-fixation. A fixation was defined to occur if the eye-tracker images showed that the point of gaze was stable (within ±2°) for ≥100ms (Patla and Vickers 1997). Handrail fixation was defined to occur if the point of gaze was within 5° of some portion of the handrail. For other fixations, we characterized the proximity of the point of gaze to the rail in terms of the nearest gaze-ellipse annulus (5-10°, 10-15°, 15-20°, 20-30° or >30°) that overlapped with some portion of the rail.

In both experiments, a three-dimensional video-based motion-analysis system (Vicon-Peak Performance, Oxford, UK) was used to characterize gross motor behaviors (grasping or touching the rail, overt reaching errors) and to determine: 1) timing of initial rail contact and grasp completion (all fingers wrapped around the rail); 2) the trajectory of the reaching motion; and 3) turning of the head toward the rail. The system comprised four cameras that provided a calibrated viewing volume (~2m high, 2m wide, 3m long), centered near the near-end of the handrail. Coordinates of reflective markers placed on the handrail, wrist and head (Experiment 1) or goggles (Experiment 2) were digitized (60Hz) and low-pass filtered (6Hz cut-off).

The trajectory of the reaching motion, relative to the handrail, was defined in terms of the lateral motion of the right wrist marker (radial styloid). Transverse-plane head rotation (yaw), relative to the rail, was based on the angle of the line segment connecting markers on the left and right temples (Experiment 1) or left and right corners of the goggles (Experiment 2). As detailed in Figure 3.1c, the latter was used in lieu of eye-tracker data (which could not be collected when the goggles were worn) to establish whether the goggle-wearing subjects had any vision of the handrail after perturbation onset. Overt motor errors were defined to occur if there was a collision between the back of the hand and the handrail, or the hand clearly overshot the rail.

Arm-reaction onset-timing was derived from surface electromyographic (EMG) recordings from the right medial-deltoid (band-pass filtered, 10-500Hz; sampled at 1000Hz).
EMG onset was determined by a computer algorithm (McIlroy and Maki 1993a) and confirmed by visual inspection. Right biceps-brachii EMG was also analyzed; however, we elected to focus primarily on the medial-deltoid (a shoulder abductor) in order to clearly identify activation associated with lateral motion of the wrist toward the rail. All EMG, kinematic and gaze timing-values were defined relative to perturbation onset (PO) as recorded by an accelerometer (platform acceleration >0.1m/s²).

3.3 Results

Experiment 1: Natural gaze behavior

Six of the 12 subjects grasped (n=4) or touched (n=2) the handrail in reaction to the platform perturbation. Although all six ultimately grasped or touched the rail successfully, three made overt errors during the initial attempt. In one case, the back of the hand collided with the rail, and overshoot errors (and subsequent reversals in wrist trajectories) were clearly evident in two subjects. The main features of the arm reactions and associated gaze behavior are summarized in Table 1. Recorded data (eye movement, head rotation, wrist displacement, medial-deltoid EMG) for example no-error and overshoot trials are plotted in Figures 3.2a and 3.2b, respectively, along with eye-tracker video-images showing the point-of-gaze at the onset of each new fixation.

The data summarized in Table 3.1 clearly show that none of the six arm reactions was guided by a fixation of the rail. This point is also illustrated by the example data plots shown in Figure 3.2. None of the six subjects were looking at the handrail at time of perturbation onset (PO). They instead fixated on the telephone (N=4), the chair (N=1), or the stair (N=1), and the visual angle from the fixation point-of-gaze at PO to any portion of the rail was never less than 10°. Four of the six subjects did make one or more saccades after perturbation onset (PO); however, none of these saccades resulted in handrail fixation. Gaze was instead redirected at the stair (subject S1 in Table 3.1), the far handrail post (S5 and S6) or the telephone (S2). The latter fixation (subject S2) was followed by an additional saccade that fixated the floor area near the chair. The remaining two subjects (S3, S4) failed to establish another stable fixation for >850 ms after PO, after which one subject looked at the floor near the chair (S3) and the other looked at the phone (S4). For all post-PO fixations, the visual angle from the fixation point-of-gaze to the handrail was never less than 5°, and the visual angle to the hand itself was never less than 20°.
In the two subjects who made post-PO fixations of the handrail post (S5 and S6), the fixation did bring a portion of the handrail itself within the central 10° of the visual field; however, these fixations began well after the initiation of the arm reaction (>125ms after the earliest arm-muscle activation). In both cases, the timing of these relatively late fixations appeared to be more closely associated with the occurrence of an overshoot error and the subsequent corrective reversal in the wrist trajectory (e.g. Figure 3.2b).

Although there was no evidence of the “eyes leading the hand” during the execution of the arm reaction, four of the six subjects who used the handrail did look directly at the rail one or more times after opening the door and entering the test environment, prior to the perturbation. Hence, “stored” central-field information about the handrail was potentially available to aid in programming the perturbation-evoked arm reaction. Remarkably, the other two subjects (S1 and S2 in Table 1) never looked directly at the rail at any time prior to rail-contact (before or after perturbation onset, PO), yet grasped or touched the rail without overt error (e.g. Figure 3.2a). The fact that the rail was never even brought within the central 5° of the visual field indicates that these two subjects relied entirely on more peripheral regions of the visual field to locate the rail.

**Experiment 2: Occlusion of peripheral vision**

Wearing the goggles that occluded peripheral vision appeared to reduce the tendency to use the handrail to recover balance. Only two of the ten goggle subjects (20%) responded to the perturbation by grasping (n=1) or touching (n=1) the handrail, in comparison to six of twelve natural-vision subjects (50%). Both of these two goggle subjects used the rail successfully (no overt overshoot or collision errors) and did so without turning their head toward the rail during the post-PO interval (yaw<5°), as illustrated by the example data shown in Figure 3.2c. The goggles were designed to force subjects to turn the head in order to acquire online (post-PO) visual information about the handrail (Figure 3.1c); hence, the absence of such head-turns indicates that the two goggle subjects who used the handrail did so despite being unable to see the rail in any portion of the visual field at any time after PO.
3.4 Discussion

This study is the first to examine the gaze behavior governing the control of perturbation-evoked reach-to-grasp reactions under natural task conditions that closely simulate the conditions in which “real-life” loss-of-balance occurs, namely: 1) a perturbation that is truly unpredictable and unexpected is delivered, 2) while the subject performs a concurrent visuo-cognitive-motor task common to daily-life (find and use a telephone), 3) while ambulating in a visually-complex environment. In contrast to the paucity of data regarding such perturbation-evoked arm reactions, a multitude of studies have examined the gaze behavior governing the control of volitional point, reach and grasp movements.

Although further work is needed to fully characterise the visual control of perturbation-evoked reach-to-grasp reactions, the initial data presented here are significant because they provide clear counter-examples to one of the prevailing principles of visuomotor control, namely, that “the eyes lead the hand” under natural task conditions (Abrams 1992; Land 2006). As such, the present data indicate a fundamental distinction between the visual control of natural volitional and compensatory (perturbation-evoked) arm movements. Presumably, the differing visual control strategies arise as a consequence of the temporal constraints that govern perturbation reactions. In order to prevent a fall from occurring, these reactions are initiated very rapidly, with arm-muscle latencies as short as 80ms, whereas the fastest latencies for volitional reaching movements are ~100ms slower, on average (McIlroy and Maki 1995b; Maki and McIlroy 1997; Gage et al. 2007). Such rapid onset timing presumably precludes the possibility of scanning the environment after PO to identify a suitable object to grasp or touch for support. Although the latencies observed here (biceps 94-234ms, deltoid 166-259ms) were not quite as rapid - likely due, in large part, to the effect of the ongoing gait-related limb movement (Quant et al. 2001) - they may still represent a significant temporal constraint on visual processing.

It has been proposed that the CNS is able to initiate an appropriately-directed limb movement so rapidly because it maintains, and continually updates, an egocentric map of the immediate surroundings (Ghafouri et al. 2004; Zettel et al. 2005; Maki and McIlroy 2007; Zettel et al. 2007). If and when a sudden unexpected “loss of balance” occurs, the “stored” visuospatial information (VSI) can be combined with multi-sensory information about the direction and velocity of the perturbation-induced body motion, so as to very rapidly initiate a reaching motion
toward an appropriate object. The present findings are consistent with this theory, as the reaching motion toward the rail was invariably initiated in the absence of a preceding visual fixation of the rail. Although it is also possible that online visual control was mediated via the peripheral visual field, the capacity to rely solely on stored VSI is supported by the results from the goggles experiment (Experiment 2). The two goggles-wearing subjects who grasped or touched the rail (without overt error) did so without turning the head toward the rail and hence had no online visual feedback (central or peripheral) about the rail location.

The degree to which this stored VSI is normally acquired from the central or peripheral fields remains to be established. The capacity to use peripheral vision is supported by the two subjects who never fixated the rail (visual angle always $>5^\circ$) at any point during the trial yet touched or grasped the rail successfully. However, the other four subjects who used the rail did fixate on it (within a $5^\circ$ visual angle) one or more times prior to PO, and hence likely used the central visual field to acquire VSI about the handrail location.

Although the results indicate that stored VSI is sufficient to guide the initial reaching motion, it appears that online feedback from the central visual field may have played a role in correcting errors in the hand trajectory during the final target-acquisition stage. The potential role of central vision in correcting trajectory errors is suggested by the timing of the post-PO fixations that brought the rail within the central $10^\circ$ of the visual field, in the two subjects who made overshoot errors. These fixations began $>250$ms prior to the completion of the grasp or touch of the handrail (e.g. Figure 3.2b), allowing ample time for online central visual feedback to guide the final target acquisition and prehension (Paillard 1996). Although neither the handrail nor the hand was foveated, the central $10^\circ$ of the visual field does encompass the macula (Flynn et al. 2003), which may have provided some relatively high-acuity visuospatial information about the rail that could have contributed to guiding the corrective action. However, it should be noted that the hand itself remained in the peripheral field (visual angle from the fixation point-of-gaze to the hand $>20^\circ$); hence, these fixations did not provide any high-acuity information about the degree to which the hand overshot the handrail.

As noted earlier, studies of volitional reaching or pointing arm movements, under natural task conditions, indicate that direct visual fixation of the target is normally used to guide the hand. It is also possible to execute such movements using “remembered” target information;
however, the consequence is a reduction in the accuracy of the end-point control (Jackson et al. 1995; Kopinska and Harris 2003; Lemay and Stelmach 2005; Heath and Binsted 2007). This is also the case when relying on peripheral vision to guide the arm motion (Bock 1986; Bock 1993; Henriques et al. 1998; Lewald and Ehrenstein 2000; Henriques and Crawford 2002). One would likewise expect a reliance on stored VSI and/or peripheral vision to compromise the accuracy of perturbation-evoked arm reactions, and this may well explain the prevalence of overshoot and collision errors, which occurred in three of six subjects in Experiment 1.

3.5 Conclusion

Although further work is needed to ascertain the degree to which peripheral vision contributes to the control of perturbation-evoked reach-to-grasp reactions, the initial results presented here demonstrate that the initiation of the reaching motion is not preceded by visual fixation of the grasp target. The motor-control principle that “the eyes lead the hand”, which is well established for volitional arm movements, clearly does not apply to these reactions. The present findings add to the literature indicating some fundamental distinctions in the CNS control of volitional and compensatory arm movements, and point to the importance of considering these distinctions during the clinical assessment and treatment of movement and balance deficits.
Table 3.1 Summary of grasping and associated gaze behavior (Experiment 1)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Type of contact</th>
<th>Contact error</th>
<th>Arm reaction</th>
<th>Visual fixation of the handrail</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Timing (ms) $^\S$</td>
<td>Prior to perturbation onset</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Deltoid onset</td>
<td>Biceps onset</td>
</tr>
<tr>
<td>S1</td>
<td>grasp</td>
<td>---</td>
<td>213</td>
<td>94</td>
</tr>
<tr>
<td>S2</td>
<td>touch</td>
<td>---</td>
<td>259</td>
<td>234</td>
</tr>
<tr>
<td>S3</td>
<td>grasp</td>
<td>---</td>
<td>166</td>
<td>179</td>
</tr>
<tr>
<td>S4</td>
<td>grasp</td>
<td>collision</td>
<td>196</td>
<td>197</td>
</tr>
<tr>
<td>S5</td>
<td>grasp</td>
<td>overshoot</td>
<td>185</td>
<td>n/a</td>
</tr>
<tr>
<td>S6</td>
<td>touch</td>
<td>overshoot</td>
<td>207</td>
<td>158</td>
</tr>
</tbody>
</table>

$^\S$ All timing values are defined in relation to perturbation onset (platform acceleration >0.1m/s$^2$). Negative values indicate events occurring prior to perturbation onset. Biceps onset time unavailable for subject S5 due to technical problems.

$^\P$ Direct fixation defined to occur if the some portion of the handrail was fixated for at least 100ms within a visual angle of 5°.
Figure 3.1. Methodological details. A. Schematic drawing of the large (2mx6m) motion platform used to evoke the reach-to-grasp reactions. B. Photograph showing the view of the platform seen by the subject after opening the door at the start of the trial (the telephone that the subject was instructed to find is located on the desk, next to the computer). C. Schematic representation of the visual field available to goggle-wearing subjects (Experiment 2). D. Example eye-tracker scene-camera video-image (Experiment 1), showing the point of gaze and visual-angle boundaries of 5°, 10°, 15°, 20°, and 30° (in the displayed image, the far end of the handrail is visible within a 15° visual angle). In C, the grey lines show the outer bounds of the visual field available to the subject and the dashed lines indicate how the nearest visual angle to the handrail was estimated based on the location of the reflective markers placed on the goggles and handrail, as determined by the motion-analysis system. A and B are adapted from Maki and McIlroy (2007), Maki et al (2008) and Scovil et al (2007).
Figure 3.2. Recorded data for example trials from Experiment 1 (panels A and B) and Experiment 2 (panel C). A shows an error-free grasp reaction (subject S1 in Table 1), while B depicts an overshoot error (subject S5). Each panel displays transverse-plane head rotation, lateral wrist displacement (relative to the handrail) and rectified EMG (right medial-deltoid). Panels A and B also display the horizontal eye movement, relative to the head (no such data are shown in C because the goggles used to occlude peripheral vision in Experiment 2 precluded use of the eye tracker). Downward displacements indicate lateral motion. The vertical lines indicate time of perturbation onset (PO), onset of deltoid activation (DO), the beginning of the closest fixation of the handrail during balance recovery (CF), initial contact with the rail (IC) and grasp completion (GC); the broken horizontal line indicates the location of the handrail in relation to the wrist marker. No grasp-completion time is shown in C because this trial involved touch contact with the rail. The inset images from the eye-tracker scene-camera, in A and B, show the point of gaze (black square symbol) at time of DO, IC and GP, and clearly indicate that the arm reaction was initiated in the absence of any direct fixation of the handrail (i.e. visual angle <5°). Although there was an early post-PO saccade in A (near time of DO), this did not result in central fixation of the rail (visual angle >15°). A more central fixation (5-10°) did occur in B, but this was much later in the response, shortly before grasp completion. The goggles worn by the subject in Experiment 2 required the head to be turned in order to see the rail during the arm reaction. In the trial shown in C, the subject touched the rail successfully in the absence of any such head turning, thus indicating that no online visual information about the rail location was needed to guide the hand.
Chapter 4
Can peripheral vision guide perturbation-evoked reach-to-grasp balance-recovery reactions?

4.1 Introduction

Historically, studies of balance-recovery reactions have tended to focus primarily on the lower limbs; however, there is an increasing awareness that rapid movements of the upper limbs also play an important role in stabilizing the body, both in daily life (Maki and McIlroy 1996; Maki and McIlroy 1997) and in experimental settings (McIlroy and Maki 1995b; Maki and McIlroy 1997; Marigold et al. 2003). While upper-limb reactions can stabilize the body through a number of inertial or gravitational mechanisms (Maki and McIlroy 1996), the largest contribution to stabilization arises when the arm motion is used to expand the effective base of support by reaching to grasp or touch an object (McIlroy and Maki 1995b). However, the visual demands of controlling these ‘compensatory’ reach-to-grasp reactions are high: it is necessary to identify and locate a suitable handhold, guide an appropriately-directed reach toward it, and grasp it, all while compensating for ongoing motion of the torso and head (Ghafouri et al. 2004). Furthermore, the urgent need to react rapidly in order to prevent a fall from occurring can impose temporal constraints that may severely limit the capacity to acquire and process the needed visuospatial information (Maki and McIlroy 2005).

One potential strategy for dealing with these temporal constraints is to use peripheral vision to guide the reaching motion, thereby eliminating the delays that would occur if instead it were necessary to execute one or more saccades in order to identify and localize a suitable handhold. The use of peripheral vision is supported by initial results from a recent study (described in Chapter 3) of natural balance-recovery behavior elicited by unexpected perturbation as subjects walked through an unfamiliar environment. Two of the six subjects who used a handrail to recover balance grasped or touched it successfully without fixating on the handrail at any time, before or after perturbation onset. Although this small sample does not allow definitive conclusions to be drawn, the results do suggest that peripheral vision may be an important source of visual information for guiding compensatory reach-to-grasp reactions.
Although no studies have systematically examined the role of peripheral vision in the control of perturbation-evoked reaching reactions, studies of volitional pointing, aiming, reaching and grasping movements have indicated that such movements can be guided using peripheral vision alone. However, the movements are invariably more accurate when central vision of the target is allowed, as forced reliance on peripheral vision leads to increased variability, as well as systematic errors (e.g. undershoot in reach amplitude) (Bock 1986; Sivak and MacKenzie 1990; Bock 1993; Henriques et al. 1998; Lewald and Ehrenstein 2000; Henriques and Crawford 2002; Schlicht and Schrater 2007) and adaptive changes in strategy (e.g. increase in grasp aperture) (Sivak and MacKenzie 1990; Goodale and Murphy 1997; Brown et al. 2005; Schlicht and Schrater 2007).

The degree to which such findings are applicable to perturbation-evoked reach-to-grasp reactions is unclear, as there are some substantial differences in task demands. In particular, the potential ‘cost’ associated with less accurate target localization is inherently more severe for the balance-recovery reactions, as the failure to grasp the target securely could well lead to a fall. Furthermore, although the CNS is clearly able to trade off speed to achieve increased accuracy when using peripheral vision to guide volitional arm movements (Binsted and Heath 2005), the need to initiate and execute the balance reaction very rapidly, as noted earlier, may allow little leeway in this regard. Conversely, it may be possible to relax the reach-accuracy demands to some extent, particularly if the target handhold is relatively large. The reach-accuracy requirements could be further reduced by using somatosensory feedback arising from the initial handhold contact to guide any final corrections needed to achieveprehension of the handhold (Salimi et al. 1999; Debowy et al. 2001; Gardner et al. 2007).

The objective of this study was to determine how the CNS resolves these speed-accuracy trade-offs when forced to rely on peripheral vision to guide a reach-to-grasp reaction evoked by an unpredictable balance perturbation. A task condition allowing full central vision of the handhold was used as a basis for comparison. Given the potential attentional demands associated with the visual processing of handhold location, we also included a task condition in which subjects performed a cognitive task that required them to maintain ‘straight-ahead’ central fixation of a computer screen. This task condition simulates the ‘real-life’ situation in which loss of balance occurs while engaged in an ongoing task that requires overt visual attention. To simulate the ‘real-life’ demands of monitoring ongoing changes in the locations of potential
handholds, we used a new ‘moveable handhold’ protocol, in which the subject is stationary and
the variation in the relative location of the handhold and body that normally occurs as a result of
ambulation is instead introduced via movement of the handhold (Cheng et al. 2008). This
approach allows precise control of visual inputs that would be very difficult to achieve using a
gait-perturbation protocol. To maximize unpredictability, the handhold was controlled to move
to, and stop at, several different ‘dwell’ positions (corresponding to pre-selected visual angles),
prior to the delivery of the balance perturbation.

We hypothesized that a forced reliance on peripheral vision would lead to some reduction
in the accuracy with which the handhold was grasped, in comparison to the central-vision
condition, but would not significantly reduce the ability to achieve a successful functional grasp.
Although we did not expect the changes in visual conditions to result in any changes in the
timing of the response initiation or completion, we did hypothesize that performing the
concurrent cognitive task would lead to a slowing of response initiation and completion, given
that such dual-task interference effects have been observed to occur even in the absence of any
visual-field restrictions (Quant et al. 2000).

4.2 Methods

Participants

Twelve young adults (6 male, 6 female; ages 22–29 years; height 1.56-1.82 m; mass 43-90 kg) participated in this experiment. Subjects were all right-hand dominant, had a minimum
corrected Snellen visual acuity of 20/40 and a minimum contrast sensitivity of 21dB (as
determined using the Melbourne Edge Test), and reported no sensory, neurological or
musculoskeletal problems. Subjects who required corrective lenses were permitted to wear them
throughout the experiment. Each participant provided written informed consent, in compliance
with the ethics approval granted by the institutional review board.

Equipment

Reach-to-grasp reactions were evoked using a large (2m x 2m) computer-controlled
platform that could translate suddenly in the horizontal plane to produce unpredictable balance
perturbations (Figure 4.1a). The subject stood in a comfortable, standardized stance position
(McIlroy and Maki 1997) near the middle of the floor. Foam blocks surrounded the feet to deter
subjects from stepping in response to the platform movement, thus reinforcing a reliance on compensatory grasping reactions (Figure 4.1b). A safety harness was worn to prevent falls.

The target handhold was a cylindrical ‘handle’ (3.2 cm in diameter, 29 cm long) which was attached to a computer-controlled apparatus that generated horizontal linear motion of the handhold in the frontal plane, as shown in Figure 4.1a (Cheng et al. 2008). The handhold and ‘handhold mover’ were positioned to the front and right of the subject and oriented such that the longitudinal handhold axis was both horizontal and parallel to the frontal plane. The handhold position was adjusted for each participant so that the height of the handhold axis was 60% of body height and the antero-posterior distance between this axis and the back of the heels was 33% of body height. To provide moderate visual contrast, the handhold was covered with medium-grey grip tape, while the visual background (floor and wall) was black. The ambient room-illumination level was ~230 lux. A black foam rubber collar was mounted at the lateral (right) end of the handhold, and used to restrict the graspable length of the handhold to 125% of the subject’s hand width. Black tape was used to form a padded cover (0.8 cm wide, 4.3 cm in diameter) over the medial (left) end of the handhold, for safety, and to clearly delineate the edge of the target region for grasping (Figure 4.1c).

A 15-inch computer monitor was mounted at the intersection of the floor and the front wall of the motion platform, 1.3 m in front of the subject (at 0° of visual angle) and tilted backward at an angle of 20° to vertical. This monitor was used to display either a static fixation point or the stimuli for the vigilance task, as detailed below. In both cases, the height of the display stimulus was adjusted such that the required downward gaze angle for central fixation of the stimulus approximated that of a point two steps ahead of the participant, a common gaze position during normal walking (Patla and Vickers 2003; Marigold et al. 2007).

Protocol

Three main task conditions were tested: 1) central vision (CV), 2) peripheral vision (PV), and 3) peripheral vision plus vigilance (PV+V). In the CV condition, subjects were simply asked to look directly at the handhold and to grasp it as quickly as possible when they felt the platform move. In the PV condition, a large (56 x 62 mm) black “X” was shown against a white background on the computer monitor mounted in front of the subject. Subjects were instructed to fixate on this “X”, and to continue doing so until it disappeared (2.0 s after the onset of the
platform perturbation). Compliance with this condition forced the subjects to rely on peripheral vision to monitor the handhold location. The PV+V trials similarly required subjects to rely on peripheral vision, but included the additional demands of performing a concurrent cognitive task. In place of the “X” displayed on the monitor during PV trials, a randomly-generated sequence of lower-case letters was displayed, one at a time, with the display changing every 250ms. Subjects were asked to count the number of times they saw the letter “h”. This display continued for 2.0s after the platform-perturbation onset. As in the PV condition, subjects were instructed to maintain fixation on the visual stimulus until the screen went blank at the end of the trial.

Compliance with the instructions regarding eye movements was monitored using a lightweight, head mounted, binocular video-based (60Hz) eye tracker (model 501, Applied Science Laboratories, Bedford, MA, USA). Subjects were informed that if they made saccades away from the fixation point during the PV or PV+V trials, their chances of winning a $50 prize for fastest reaching performance (described in more detail below) would be reduced.

After completing four practice trials (to ensure that the subject understood the task conditions), each subject performed five blocks of trials. Each trial block comprised 18 perturbation trials (3 task conditions x 2 perturbation directions x 3 final handhold locations), plus one to three ‘catch’ trials in which the platform did not move. The order of trials within each block was randomized.

In each trial, the handhold started at a ‘home’ position to the right of the subject’s midline, at a visual angle greater than 55°. Prior to the onset of each platform perturbation, the handhold was controlled to make one to four discrete movements, with each movement ending at one of seven possible ‘dwell’ positions, where the handhold would pause for 0.5-3.0s before moving to the next position. Each handhold motion took 0.4-1.3s to complete, with the maximum handhold velocity limited to 0.480m/s. Platform acceleration began between 1.0-3.0s after the handhold reached its final position. Three final handhold positions were tested, corresponding to visual angles of 20°, 30° and 40° (as measured to the medial end of the grey target region of the handhold, relative to the right eye). The intermediate ‘dwell’ positions also included visual angles of 15°, 25°, 35° and 45°. The three final positions were determined, using standard anthropometric data (Winter 1990; Tilley and Henry Dreyfuss Associates. 2002), to
correspond approximately to shoulder-handhold distances of 37%, 38% and 42% of body height, respectively, when the subject is standing upright in the starting position.

Two perturbation directions were tested, involving: 1) forward platform translation (acceleration amplitude 1.15 m/s²; maximum velocity 0.35 m/s; displacement 0.10 m) which induced backward falling motion, and 2) backward translation (acceleration amplitude 1.75 m/s²; maximum velocity 0.53 m/s; displacement 0.16 m) which induced forward falling motion. In each case, the waveform comprised a 300 ms approximately-square acceleration pulse, followed immediately by an equal and opposite deceleration pulse. In 10% of trials, the platform did not move. These ‘catch’ trials were included to discourage anticipatory initiation of the arm movement and were delivered most frequently early in the test session to reinforce to the subject that the platform would not necessarily move in every trial.

Subjects were instructed to recover balance by grasping the grey region of the handhold as quickly as possible after the onset of the platform motion. They were also told not to move their feet. Additional motivation to produce rapid grasping responses was provided in the form of a $50 prize, awarded to the subject who achieved the quickest average response time. Subjects were asked to start with arms relaxed by their sides and hands forming ‘loose’ fists (all digits relaxed, fingers flexed with the thumb ‘on top’), and were instructed not to move their arms or hands until they could feel the floor move. They were told that premature initiation of arm movements would result in a penalty that reduced their chances of winning the $50 prize.

To prevent use of auditory cues to aid in detecting or tracking handhold motion, subjects wore headphones that played masking noise (recordings of sounds made by the handhold mover) throughout the duration of each trial. To simulate the directionality of the handhold-mover sounds, the masking sounds were only played through the right headphone speaker. The volume was tuned through pilot testing to be approximately equivalent to the volume of noises made by the handhold mover, as perceived while wearing the headphones.

Data Collected

The arm reactions were recorded by four video cameras, three located overhead and one located to the far left of the subject and aligned approximately with the handhold axis. These recordings were used to classify reactions as to whether ‘successful’ grasping of the rail occurred
and whether the reaching movement was accurate (on target). The final position of the hand was deemed to represent a ‘successful grasp’ if one or more digits was wrapped around the rail. A response was considered on-target if the final hand position placed the entire handwidth within the grey portion of the handhold, per the subject instructions. Off-target responses included: 1) grasping the medial end of the handhold, with some portion of the hand extending beyond the edge of the grey target area; 2) collision of the hand with the black foam barrier located at the lateral end of the handhold; or 3) collision of the back of the hand, thumb or fingers with the rail.

Electromyographic (EMG) recordings from the right medial-deltoid muscle were band-pass filtered (10-500Hz) and sampled at 1000Hz. EMG onset latency was determined by a computer algorithm (McIlroy and Maki 1993a) and confirmed by visual inspection. Force-sensing resistors mounted on the front, back and top surfaces of the handhold were sampled at 200 Hz and used to identify the time of handhold contact. These timing measures were all defined relative to onset of perturbation (platform acceleration >0.1m/s²).

Kinematic data for the right arm and hand, collected at 200Hz using a three-dimensional optoelectronic (infrared) motion-analysis system (Motus 8, Vicon-Peak Performance, Oxford, UK), were used to characterize the reach trajectories in more detail. Reflective markers were placed on the right shoulder (acromion process), wrist (styloid process), and hand (distal end of the 3rd metacarpal). The recorded coordinates for these markers were low-pass filtered at a cut-off frequency of 6Hz using a dual-pass fourth-order Butterworth filter (Gage et al. 2007). The following kinematic measures were then determined for the right wrist (relative to the right shoulder): maximum resultant velocity, time to maximum velocity (in relation to deltoid onset), total movement time (time from deltoid onset to handhold contact), time to maximum velocity expressed as a percentage of the total movement time, and duration of the deceleration phase.

Statistical Analysis

Repeated-measures analysis of variance (ANOVA) was performed to assess the main effect of task condition on each of the four primary variables used to characterize the speed-accuracy trade-offs: 1) frequency of successful grasping, 2) frequency of accurate reaching, 3) onset timing of the deltoid activation, and 4) handhold contact time. Perturbation direction and handhold location were included as additional factors within the ANOVA. Significant two- or three-way interactions were interpreted by performing post hoc one-way analyses (repeated-
measures ANOVA and Tukey multiple comparisons), so as to determine the effect of task condition within each of the six possible combinations of perturbation-direction and handhold-location. Secondary kinematic measures were also analysed using the same statistical model. All data were rank-transformed prior to analysis. This procedure avoids errors arising from potential violations of the assumptions underlying the ANOVA model, and is equivalent to performing a non-parametric test (Conover and Iman 1981).

For the frequency variables, the proportion of trials in which the event was observed was calculated within each subject, for each of the 18 experimental conditions (3 task conditions x 2 perturbation directions x 3 handhold locations), and the ANOVA was performed on the rank-transformed proportions. For all of the other variables, rank-transformed data from individual trials were analyzed. Trials in which subjects initiated the arm movement prematurely (EMG onset latency <40ms; (Maki et al. 1998)) and PV or PV+V trials in which the subject executed one or more saccades toward the handhold were excluded from the analysis. In addition, 101 trials were excluded from the primary analyses and 87 from the secondary analyses due to technical problems.

4.3 Results

Compliance with the task instructions was very high. For the task conditions that required subjects to use peripheral vision to monitor the changes in the location of the handhold, saccades away from the fixation point occurred in only 9% (34/360) of PV trials, and 1% (4/360) of PV+V trials. The incidence of prematurely initiated arm movements (EMG latency<40ms) was also very low. This occurred in a total of only 3 trials across all subjects. Reaches toward the handhold occurred in over 99% (1007/1015) of trials, and subjects were able to achieve a functional grasp of the handhold in more than 90% of trials (mean within-subject ‘functional-grasp’ frequency ±SD: 93±18%). As hypothesized, the functional-grasp success rate was not affected by task condition (F2,22=1.72; p=0.20; Figure 4.2a).

The accuracy of the reach, i.e. the ability to land the hand within the designated target area on the handhold, was somewhat lower (mean success rate of 75±23%). In line with our hypotheses, the reach-accuracy success rate did show a main effect due to task condition (F2,22=4.62; p=0.021); however, there was a significant three-way interaction between task condition, perturbation direction and final handhold position (F4,44=3.12; p=0.025) which
complicates interpretation of these data. As illustrated in Figure 4.2b, there was a trend for the reach-accuracy success rate to be lowest in PV+V trials, but this trend was largely limited to the most peripheral handhold location (40° visual angle). For this handhold location, the reach-accuracy success rate was only 56±26% in PV+V trials, in comparison to rates of 69±28% and 73±22% in the PV and CV trials, respectively. Between-subject variability was large, however, and post-hoc comparisons of means (α=0.05) failed to provide any evidence that this trend was statistically significant.

Analyses of the timing measures showed a minimal effect of task condition on the timing of deltoid onset latency, but a far more pronounced effect on the time to handhold-contact. Deltoid latency did not exhibit any statistically significant main effects due to task condition (F_{2,22}=1.41; p=0.27); however, the three-way ANOVA did reveal a significant interaction (task X perturbation-direction; F_{2,22}=4.68; p=0.02). Post hoc investigation of this interaction showed the only significant effect of task to be a slightly faster onset time when the handhold was viewed in PV (134±32ms) rather than CV (151±42ms) for a handhold location of 20° during forward ‘falls’ (Figure 4.2c).

In contrast to the absence of strong task effects for deltoid latency, task condition had a highly significant main effect on handhold-contact time (F_{2,22}=119; p<0.0001). Again, however, interpretation of this result was complicated by the presence of a significant interaction (task X handhold-location X perturbation-direction; F_{4,44}=6.26; p=0.0004). As illustrated in Figure 4.2d, the most pronounced task effects occurred when the handhold was in the 40° position. For both ‘fall’ directions, post hoc comparisons (α=0.05) showed that contact of the handhold in this location occurred significantly later (by ~90ms, on average) in the PV+V trials than in the CV trials. This same pattern was evident for all handhold positions and both ‘fall’ directions, and was statistically significant in two cases (30°/forward-fall, 20°/backward-fall); however, the differences between PV+V and CV trials were less pronounced than in the 40° trials. Mean handhold-contact times for responses executed in the PV condition tended to be intermediate to the CV and PV+V contact times, and differed significantly (α=0.05) in three cases (PV>CV for 40°/backward-fall and 30°/forward-fall trials, PV<PV+V for 40°/forward-fall trials).

Secondary analyses were performed on selected kinematic measures, in an effort to gain further insight into task-related differences in the control of the reach-to-grasp reactions.
Maximum wrist velocity was found to be similar for all task conditions (PV 2.69±0.61 m/s, PV+V 2.62±0.59 m/s, CV 2.74±0.64 m/s; F\(_{2,22}\)=2.29, p=0.13), across all handhold positions and both perturbation directions (no significant interactions, p’s>0.23). In contrast, task condition did have a main effect on movement time, with faster movements occurring in the CV trials than in either of the peripheral-vision conditions (PV 331±142 ms, PV+V 348±120 ms, CV 297±87 ms; F\(_{2,22}\)=21.2; p<0.0001); however, a significant three-way interaction (F\(_{4,44}\)=4.49; p=0.004) and post hoc comparison of means (α=0.05) showed that this effect was largely limited to final handhold locations of 30° and 40° (for the 20° location, the only significant difference was a slower movement time in PV+V versus CV trials, during backward ‘falls’).

Time-to-maximum-velocity also varied significantly between task conditions (F\(_{2,22}\)=7.68, p=0.003); however, the analysis of this variable also showed a significant three-way interaction (F\(_{4,44}\)=3.34; p=0.020). Post hoc comparison of means (α=0.05) indicated that the maximum velocity occurred significantly earlier (by ~40 ms) in CV trials, in comparison to PV+V trials, in two cases (40°/forward-fall, 20°/backward-fall). This trend was reversed when the time-to-maximum-velocity was expressed as a proportion of the total movement time. The latter analysis showed a significant main effect due to task (F\(_{2,22}\)=8.82; p=0.0015), without significant interactions (p’s>0.11), and post hoc comparisons of means (α=0.05) indicated that the maximum velocity occurred significantly earlier, as a proportion of total movement time, in both peripheral-vision conditions (PV and PV+V). This difference, viewed in terms of absolute deceleration times, also showed a highly significant main effect of task (F\(_{2,22}\)=23.25, p<0.0001), with CV values consistently less than those in either peripheral-vision condition (PV 138±131 ms, PV+V 140±103 ms, CV 106±68 ms). However, interpretation was complicated by a significant interaction (task X handhold-location; F\(_{4,44}\)=3.20; p=0.022). Post-hoc investigation of this interaction showed a trend for these differences to increase as the handhold was viewed at higher visual angles. Although the mean differences in time-to-maximum-velocity were statistically significant, it should be noted that the magnitudes of the differences were relatively small, for both the absolute timing data (PV 348±65 ms, PV+V 370±84 ms, CV 346±58 ms) and the relative timing expressed as a proportion of total movement time (PV 70±23%, PV+V 72±23%, CV 76±20%).
4.4 Discussion

As hypothesized, the frequency of successful grasping reactions was very high (>90%) and was unaffected by whether central or peripheral vision was used to locate the handhold, or by the attentional demands of engaging in a concurrent visuo-cognitive task. This finding is consistent with our expectation that the CNS would prioritize achieving successful functional contact with the handhold, regardless of task condition, in order to safeguard postural stability. However, we also expected that the reduction in spatial acuity in peripheral-vision trials would force the CNS to sacrifice reach accuracy to some extent, in order to preserve a rapid speed of response. This hypothesis was not entirely supported by the findings. Although, in general, it was possible to use peripheral vision to achieve a comparable degree of reach accuracy without sacrificing speed in initiating or completing the reach, evidence of a substantial decrement in speed (~75ms delay in handhold-contact time) when reliant on peripheral vision did emerge in the most challenging condition, i.e. when the handhold was located in the extreme periphery and the subject was falling backward (away from the handhold). Consistent with our final hypothesis, the concurrent task did appear to exacerbate the delay in contacting the handhold, but there was no support for our expectation that the response initiation would also be slowed under this task condition.

Given the absence of any task effects on response initiation (deltoid latency), it follows that the aforementioned delays in handhold-contact time must be due to a slowing in movement time. Explicit analysis of the movement-time data confirmed that reaches guided by peripheral vision to handhold locations of 30° and 40° took significantly longer than the equivalent reaches guided by central vision. The root cause of these delays may be a lower spatial resolution in the periphery because this increases the level of uncertainty regarding target location. While this did not lead to any significant declines in reach accuracy, the increased time required to complete the reaction may have been caused by a need to compensate for the uncertainty in target location by approaching the handhold more slowly, allowing for the use of online corrections to compensate for poor accuracy in the initial reach targeting.

An increased time to contact the grasp target when dependent on peripheral vision has also been reported in a study of volitional reach-to-grasp (Sivak and MacKenzie 1990); however, that study found a much larger mean delay (~500ms) in comparison to the largest mean delay
seen in our data (75ms). A number of methodological differences may have contributed to the difference in effect size, including the higher accuracy requirements of their precision pinch-grip task and the fact that the volitional-reach subjects were not instructed to reach as rapidly as possible. More generally, however, there is an intrinsic and very real cost (i.e. falling) associated with increasing the movement time too much during compensatory reach-to-grasp reactions, and this cost is likely to the main factor that drives the CNS to limit any timing delays. Such a cost cannot be readily replicated in studies of voluntary movement.

In the study by Sivak and Mackenzie (Sivak and MacKenzie 1990), the majority of the additional time taken to grasp the target when dependent on peripheral vision occurred during the deceleration phase of the movement, after the peak in wrist velocity. Presumably, the prolongation of the deceleration phase serves to ‘buy’ the additional time needed for online corrections to the arm trajectory, as has been suggested in other studies of volitional pointing and reaching movements (Khan et al. 2006). The size of the mean difference (PV minus CV) was actually three times larger in our study (8% versus 2.4%), when the time-to-peak was expressed as a proportion of total movement time; however, in absolute terms, our effect size was much smaller, due to the fact that our perturbation-evoked reactions were much more rapid. Thus, our mean deceleration-phase duration was 105ms in central-vision trials and 139ms in peripheral-vision trials, whereas the corresponding values in the study by Sivak and Mackenzie were 712ms and 1069ms. Nonetheless, studies of volitional reaction-time pointing and reaching movements suggest that the mean increase in deceleration-phase duration observed in our PV trials (34ms) may be sufficient to facilitate the execution of online trajectory corrections (Paillard 1996).

The delays in handhold-contact time associated with the dependence on peripheral vision tended to be exacerbated when subjects performed the concurrent visuo-cognitive task. Although the difference between the PV and PV+V tasks was statistically significant in only two experimental conditions (forward falling motion, 40° handhold location; backward falling motion, 20° handhold location), the addition of the cognitive task increased (from two to four) the number of conditions in which the peripheral- and central-vision handhold-contact times differed significantly. In terms of effects on the accuracy of the response, a functional level of grasp accuracy was almost always achieved. The success rate with which the hand was placed within the specified target region of the handhold appeared to drop by a modest amount (mean ~15%) in the PV+V trials, when the handhold was at the 40° location, but this was not
statistically significant. Overall, these results suggest that the concurrent cognitive task had a modest effect, at most, on the speed and accuracy of reaches guided using peripheral vision.

We had also expected the addition of the cognitive task to significantly delay reaction initiation, based on previous findings that a mental arithmetic task (counting backward by serial 7’s) led to a 40ms delay in deltoid latency during reach-to-grasp reactions evoked by chair-tilt perturbations (Quant et al. 2000); however, we found no evidence to support such an effect. The discrepancy in findings could possibly be due to differences in the nature of the cognitive task and/or method of perturbation. We are not aware of any other studies that have examined the effects of cognitive tasks on upper-limb balance reactions; however, there have been a substantial number of dual-task studies involving lower-limb balance reactions. Our results are consistent with these studies, which have generally found that competing attentional demands tend to affect later phases of the balance-recovery reactions, but not the initiation phase (Maki and McIlroy 2007).

The findings of the present study are likely dependent, at least to some extent, on the specific handhold dimensions and perturbation characteristics that were used. Clearly, larger perturbations would place greater demands on the speed of response, whereas a smaller handhold would increase demands on accuracy. Given that the specific handhold that we used is much smaller than the handrails and grab-bars that are typically found in ‘real-life’ environments, the capacity of our subjects to use peripheral vision to grasp a relatively small target such as this would suggest that peripheral vision may well play an important role in guiding reach-to-grasp reactions in ‘real-life’ environments. With regard to the perturbations, we elected to use relatively small perturbations in this initial study, in order to prevent stepping reactions from being evoked. Further work will be needed to determine whether the increased speed-of-response demands imposed by larger perturbations will affect the degree to which peripheral vision can be used to guide reach-to-grasp reactions.

The ‘moveable handhold’ paradigm was used in this study in order to avoid a number of methodological problems associated with more ‘ecologically valid’ approaches to studying the visual control of balance-recovery reactions. Such approaches would involve applying a balance perturbation as the subject moves within the environment, and recording the gaze behaviour that occurs. While we have used this approach in previous and ongoing studies (Scovil et al. 2007;
King et al. in preparation; Lee et al. in preparation), there are a number of practical limitations: 1) variation in gait precludes precise control over the position and motion of the body, in relation to the handhold, at perturbation onset; 2) this variation also precludes precise control of central and peripheral visual inputs; 3) subjects are likely to learn proactive, adaptive strategies after a small number of trials. The ‘moveable handhold’ approach avoids these problems by having the subject remain stationary and moving the handhold to introduce the relative motion that would normally occur as a result of ambulation.

However, this ‘moveable handhold’ approach has its own limitations that may potentially limit the generalizability of the findings to ‘real-life’ loss-of-balance situations. For example, the perturbations, while unpredictable in timing and direction, were nonetheless fully expected by the subjects, whereas the ‘real-life’ perturbations that precipitate falls are likely to involve unexpected events. Furthermore, the administration of multiple trials provided opportunities for learning and adaptation (McIlroy and Maki 1995a) that would not be available in typical ‘real-life’ loss-of-balance situations. Another limitation pertains to the intermittent nature of the handhold motion and the predictability of certain features of the handhold location (e.g. height and frontal distance, maximum extent of handhold motion), whereas the relative motion between subject and handhold that occurs as a result of ambulation in daily life leads to continuous, and much greater, variation in relative handhold location. Finally, although we did simulate the effect of the competing attentional demands that would be likely to occur in daily life, the simplicity of the test environment minimized the attentional demands of the ‘visual search’ that would normally need to be carried out to locate a handhold in the periphery.

The findings of this study contribute to increasing our understanding of the CNS control of rapid balance-recovery reactions, and also provide a baseline for future studies which will address the effects of factors such as aging, sensorimotor disorders, neurological disease and medication use. It will also be possible to use this paradigm to investigate the efficacy of clinical interventions, such as the “visual-training” programs we are currently studying (McKay et al. 2008) or the effects of wearing contact lenses, bifocals or other types of visual aids. Studies of older adults are expected to be particularly important in relation to the problem of falling, because it is known that the capacity of many older adults to use peripheral vision is limited by either sensory or attentional impairments (Owsley et al. 1995; Sekuler et al. 2000; West et al. 2002; Cedrone et al. 2008). Given the evidence suggesting that use of peripheral vision to guide
compensatory reach-to-grasp balance-recovery reactions is a naturally-adopted strategy in healthy young adults (King et al. in preparation), the capacity to better understand, and counter, the impaired ability to use this strategy may ultimately help to reduce risk of falls for older adults.

4.5 Conclusion

The results of this study indicate that peripheral vision can be used to guide rapid perturbation-evoked reach-to-grasp reactions with a level of accuracy that is sufficient to achieve a functional grasp, even when the size of the handhold is relatively small and the location of the handhold is varied in an unpredictable manner prior to perturbation onset. These peripherally-guided reactions were executed as rapidly as responses that were guided by continuously-available central vision of the handhold, provided that the handhold eccentricity was low (20°); however, movement times increased significantly with degree of eccentricity, leading to a substantial delay (~75ms, on average) in contacting the handhold at the highest visual angle (40°). Performance of an ongoing cognitive task had relatively little impact on the ability of the CNS to react quickly and accurately to grasp the handhold under the guidance of peripheral vision. Given that it is quite common for people to be engaged in an ongoing attention-demanding task when they lose their balance, our findings support the idea that, for healthy young adults, peripheral vision can be a sufficient source of information for guiding rapid compensatory reach-to-grasp reactions in many daily-life situations.
**Figure 4.1** Methodological details: **A** gives an overview of the experimental environment, and shows how the handhold position was adjusted relative to each subject's height (H). **B** shows a subject standing in this environment, grasping the handhold. Foam blocks placed around the feet restrict stepping, reinforcing reliance on reach-to-grasp reactions. **C** shows the target region of the handhold, with black tape delineating the medial end of the target region and a black foam barrier forming the lateral boundary of the target. The location of the foam barrier was adjusted for each subject such that the target region was 125% of the subject’s hand width.
Figure 4.2: Effect of task condition on the primary variables

These graphs show mean values for each of the primary variables per the one-way post hoc ANOVAs and multiple comparisons (α=0.05). Mean effects of task condition are shown for each fall-direction X handhold-location combination. Error bars indicate the standard deviation. Panels A and C show the consistency of functional-grasp frequency and deltoid onset timings. Note that in B, while none of the comparisons is significant, there is a trend to decreased accuracy in the PV+V condition when the handhold is located at the highest visual angle. In D, differences in handhold contact times are shown. Note the trend for increased times to handrail contact in the PV+V condition (and to a lesser extent for the PV condition), as compared to CV. As shown, this trend was most pronounced at the highest visual angle.
Chapter 5
General Discussion

5.1 Discussion of Contributions

The thesis increases our understanding of the visuomotor control of an important element of the postural control repertoire, namely, perturbation-evoked reach-to-grasp balance-recovery reactions. Specifically, the thesis addressed three main questions that have not been addressed in previous work: 1) what visual information guides rapid compensatory reach-to-grasp reaction in daily life; 2) how well peripheral vision can guide perturbation-evoked reach-to-grasp reactions; and 3) how an ongoing cognitive task influences perturbation-evoked reach-to-grasp performance for targets seen in the visual periphery.

5.1.1 What visual information guides rapid compensatory reach-to-grasp reactions in daily life?

Our study of natural gaze behaviour during recovery from an unexpected loss of balance found that subjects who touched or grasped the handrail as part of their balance recovery strategy did not fixate on it at any time during the reaction, relying instead on stored visual-spatial information acquired prior to perturbation onset, online peripheral vision or some combination of thereof to guide their responses. This finding provides a clear counter-example to one of the prevailing principles in visuomotor behaviour, namely that the “eyes lead the hand” under natural task conditions (Abrams 1992; Land 2006). When no instructions are given regarding gaze behaviour, a saccade to the target is typically initiated either slightly before or in parallel with a voluntary limb movement and gaze reaches the target well in advance of the limb. However, a difference between these volitionally-initiated tasks and the perturbation-evoked reactions examined in this thesis is the cost of delays in response initiation. The urgent need to response to a loss of balance places very high demands on the speeds of response initiation and execution because to prevent a fall effectively, a reach-to-grasp must be initiated very rapidly following the detection of instability. This level of urgency is not generally present for volitionally-executed movements. While no subjects fixated directly on the handrail during balance recovery, two subjects of the six subjects who used the handrail to recover balance did
fixate within 10° of some portion of the rail. The timings of these fixations, which began ~250-300 ms prior to stable contact being made with the handrail, presumably served to allow central vision to aid in guiding the final phases of the touch or grasp.

Remarkably, two of the six subjects who used the handrail to recover balance never fixated directly on it, at any point prior to or during balance recovery. One of these subjects never fixated within 5° of the rail prior to perturbation onset nor within 10° during balance recovery; the other never fixated within 10° of the handrail prior to perturbation onset nor within 15° during balance recovery. Clearly, these subjects were able to rely on peripheral vision of the handrail to guide their compensatory reach-to-grasp reactions. While the subject numbers are too low to allow any definite conclusions to be drawn, it is worth noting that neither of these subjects committed overt errors in executing their touching and grasping reactions. This finding therefore provides initial evidence that for healthy young adults, peripheral vision may provide sufficient visual-spatial information to guide rapid, functional reach-to-grasp balance-recovery reactions.

Stored central visual information was also found to be a sufficient source of visual-spatial information to guide grasping responses in the absence of online vision of the target. This was found in the second experiment presented in Chapter 3, in which subjects wore goggles that blocked the peripheral field while walking through an unfamiliar, complex environment. These subjects had no vision of the handrail during balance recovery, yet they were able to use the handrail without overt error as part of their balance recovery strategies. More remarkably, they stored visual information about the handhold location prior to loss of balance, despite the fact that there was no expectation that they would be perturbed. This provides support for the idea that the CNS automatically maintains an egocentric visual-spatial map of features of the environment which could aid in balance recovery, as a contingency in case of a sudden loss of balance (Ghafouri et al. 2004; Zettel et al. 2005; Maki and McIlroy 2007; Zettel et al. 2007).

5.1.2 How well can peripheral vision guide perturbation-evoked reach-to-grasp reactions?

This thesis presents evidence that, for healthy young adults, peripheral vision can be a sufficient source of information for guiding perturbation-evoked reach-to-grasp reactions. Evidence presented in Chapter 4 showed that the reach accuracy to targets viewed only in
peripheral vision (visual angle range 20°-40°) did not differ significantly from when central vision of the targets was available. However, while there were no differences in response initiation latencies, the movement times for responses guided by peripheral vision at the higher visual angles studied (30° and 40°) were found to be significantly longer than when reaches were guided by central vision. While this difference was relatively small (<30ms, on average) when the handhold was at 30°, it rose to ~75ms when the handhold was viewed at 40°. Together, these results imply that the CNS sacrifices some speed to ensure that a functional grasp is achieved when executing compensatory reach-to-grasp reactions.

Further investigations of the velocity profile of the wrist revealed that the deceleration times were longer for reaches guided by peripheral vision (at angles ≥30°) than for those guided by central vision, allowing more time for online trajectory corrections to be made. Because spatial resolution is known to decline with increasing retinal eccentricity (Post and Johnson 1986), an increase in the level of uncertainty regarding target location for peripherally-viewed targets is expected compared to when central vision is used. This expectation is supported by the numerous studies of voluntary pointing, aiming, reaching and grasping movements guided by peripheral vision, which have found that that directional accuracy is lower than when central vision of the target is allowed (Bock 1986; Sivak and MacKenzie 1990; Bock 1993; Henriques et al. 1998; Lewald and Ehrenstein 2000; Henriques and Crawford 2002; Schlicht and Schrater 2007). It therefore seems likely that the increased time required to complete perturbation-evoked reach-to-grasp movements guided by peripheral vision resulted from a greater need to use online trajectory corrections to compensate for poor accuracy in the initial reach targeting.

5.1.3 How does an ongoing cognitive task influence perturbation-evoked reach-to-grasp performance for targets seen in the visual periphery?

The results presented in this thesis showed that performance of an ongoing visual-cognitive task had relatively little impact on the ability of the CNS to react quickly and accurately to grasp a peripherally-viewed handhold. While the success rate for achieving a functionally useful grasp was unaffected, the ability to grasp the ‘target zone’ of the handhold did decrease by a modest amount (mean ~15%) when the handhold was viewed at the most eccentric (40°) location, although this result was not statistically significant. The addition of a cognitive task also had no impact on initiation time and a minimal impact on the timing of reach completion.
A previous study which examined the effect of a mental arithmetic task (counting backwards by serial 7’s) on the latency of reach-to-grasp reactions evoked using chair-tilt perturbations found that the cognitive task causes a significant delay (~40ms) in deltoid onset (Quant et al. 2000); however, no evidence of such a delay was found in our results. This discrepancy in findings could be due to differences in the nature of the cognitive task and/or method of perturbation used - both of these factors differed substantially between the two studies. Furthermore, the previous study did not impose any restrictions on gaze direction and the location of the handhold was static and predictable; therefore, it is not clear to what extent the central and peripheral visual fields were used to guide the reaction. While we are not aware of any other studies which have examined the effect of an ongoing cognitive task on reach-to-grasp reactions, a substantial number of dual-task studies involving lower-limb balancing reactions have been performed. These studies have typically found that competing attentional demands do not affect the initiation of balance-recovery reactions, although they do delay later phases of the response (Maki and McIlroy 2007). This is the pattern of results which was found in our peripheral vision study.

5.2 Limitations

Each of the two experimental paradigms employed in this thesis has limitations which restrict the generalizability the findings; however, the two approaches are complementary and the strengths of each approach tend to offset the weaknesses of the other. The ‘ecologically valid’ approach used in the first study allows natural behaviours to be observed at the expense of close control over subject motion, position and sensory inputs; the ‘handhold mover’ paradigm used in the second study controls for these factors at the expense of limiting the unpredictability of the handhold location and postural perturbations.

The primary focus of the study presented in Chapter 3 was to identify the gaze behaviours naturally used to guide compensatory grasping responses in daily life. To simulate a natural situation, the large motion platform used to deliver postural perturbations was configured to resemble a visually-complex, “real-life” living environment. Subjects were asked to perform a typical task of daily life that required a visual search while walking through this environment. A deception was employed to ensure that the perturbation was not expected. While this paradigm did allow natural gaze behaviours to be observed, the measures taken to allow natural
behaviour and to ensure that the perturbation was truly unexpected required sacrificing control over: 1) the position and ongoing motion of the body, due to variations in gait; 2) precise control of the availability and timings of central and peripheral visual inputs; and 3) what balance recovery response the subject used (including whether and in what way they attempted to use the handrail). In order to avoid the effects of learning and adaptation (Horak and Nashner 1986; McIlroy and Maki 1995a; Pavol et al. 2004), it was also necessary to limit analysis to the first trial for each subject. As a result of the diversity of gaze behaviours and response strategies, combined with the high variability in subject kinematics, there is a limit to the depth of analysis that could usefully be performed on data from these studies. However, this limitation does not detract from this study’s primary focus, namely the identification of the gaze-grasp behaviours which are naturally adopted by young adults in response to unexpected postural perturbations. That being said, a series of well-controlled follow-up experiments is required to understand the efficacy of each gaze strategy for controlling reach-to-grasp reactions. In addition, testing of much larger samples is needed to determine the prevalence of each type of gaze strategy.

The experiment presented in Chapter 4 is the first of a planned series of well-controlled experiments to investigate the various gaze strategies adopted by young adults for the control of compensatory reach-to-grasp reactions. For this study, a newly-developed ‘handhold mover’ paradigm was used (Cheng et al. 2008). This approach avoids the limitations of the more ‘ecologically valid’ approach used in the first study by having the subject remain stationary and moving the handhold to introduce the relative motion between subject and handhold that would normally occur during ambulation. However, there are new limitations introduced by the measures required to establish this increased control over the subject’s position, ongoing motion and visual inputs. Firstly, while the direction and timing of the perturbations were unpredictable, loss of balance was fully expected. The perturbations were also repeated, allowing the subject the opportunity to adapt to the perturbation characteristics (Horak and Nashner 1986; McIlroy and Maki 1995a; Pavol et al. 2004). The limited variation in handhold location (i.e. the constant height, orientation and antero-posterior distance; restrictions on the extent of handhold motion; and the intermittent nature of this motion) also affects the ecological validity of the study – the relative motion which occurs between a subject and potential handholds in daily life is generally continuous and includes far greater spatial variation than could be simulated using this paradigm. A further limitation of this study is that although we did simulate the effect of the competing
attentional demands that would be likely to occur in daily life through use of a vigilance task, the simplicity of the test environment minimized the attentional demands of the ‘visual search’ that normally needs to be carried out to locate a handhold in the periphery.

The generalizability of these findings is also limited by the handhold characteristics and perturbation magnitude used for this experiment. Under the selected conditions, the CNS was able to maintain high levels of functional accuracy for all task conditions, apparently at the cost of some reduction in the speed of response for movements guided by peripheral vision. However, the use of a different handhold size would affect the speed-accuracy tradeoffs made by the CNS to optimize the chances of regaining balance successfully. As compared to the handholds and grab-bars typically found in ‘real-life’ environments, the target handhold employed for this experiment was relatively small. Consequently, the success of our subjects in localizing and grasping that target using only peripheral vision implies that this may indeed be a feasible balance-recovery strategy to employ in daily life. However, our perturbation magnitude was quite low, to ensure that subjects did not use stepping reactions as part of their balance recovery strategies. It may be that at higher perturbation magnitudes the use of peripheral vision to guide compensatory reach-to-grasp reactions becomes less feasible due to heightened demands on the speed of response required to avoid a fall. This may lead to increased grasp failure rates, especially at higher visual angles. Further work is necessary to investigate this possibility.

5.3 Practical Applications

The collected findings of this thesis contribute to the understanding of how the CNS controls rapid reach-to-grasp balance-recovery reactions. In addition to the intrinsic value of these findings for understanding how the central nervous system uses vision to control balance-recovery reactions, they provide a baseline for the evaluation of the effects of aging and of sensorimotor and neurological deficits on the control of balance recovery responses. A comparison of the different natural gaze and grasping strategies adopted by young and older adults will provide information on how ‘choice’ of balance-recovery response, and the efficacy of the selected response, is influenced by aging. Differences in the strategies selected will also help to identify the most useful directions for further research to understand the effects of aging on how vision is acquired and used to guide balance recovery reactions. Furthermore, these
differences could indicate the types of interventions which would best facilitate handrail localization and use for older adults. The baseline young adult data provided by the peripheral vision experiment using the handhold mover paradigm can serve as a useful basis for evaluating changes in the ability to use peripheral vision to guide balance recovery due to factors including aging, sensorimotor disorders, neurological disease and medication use. This standardized, well-controlled protocol can also be used to investigate the efficacy of clinical interventions, such as the “visual-training” programs we are currently studying (McKay et al. 2008). Studies of older adults are expected to be particularly important in relation to the problem of falling, since it is known that the capacity of many older adults to use peripheral vision is limited by either sensory or attentional impairments (Owsley et al. 1995; Sekuler et al. 2000; West et al. 2002; Cedrone et al. 2008). Given the collected evidence presented by this thesis, indicating that the use of peripheral vision to guide compensatory reach-to-grasp balance-recovery reactions is an effective naturally-adopted strategy for healthy young adults, the capacity to better understand and counter any impairments affecting the ability to use this strategy may ultimately help to reduce risk of falls for older adults.

5.4 Future Work

This thesis contributes to the as yet limited body of research directed toward understanding the visual control of rapid reach-to-grasp balance-recovery reactions. In doing so, this thesis highlights many areas about which little is currently known. The study natural gaze patterns used by young adults to guide balance recovery (Chapter 3) identifies the gaze strategies which are relied upon under natural balance recovery conditions, and which would be most useful to understand in more detail. The first study to follow up on the findings of this natural gaze experiment is the investigation of the efficacy of using peripheral vision to control reach-to-grasp reactions which is presented in Chapter 4 of this thesis. However, the other strategies identified, namely exclusive reliance on stored visual information and the combined use of stored central and online peripheral vision, should also be investigated in more detail. Outstanding questions in this area include (but are by no means limited to): how long it takes to acquire sufficient visual information to localize a grasp target, how persistent this visual representation is (i.e. how the accuracy of the representation decays with time), how the quality of the representation is affected by natural ongoing movements of the body and head, and what influence an ongoing cognitive task has on the formation, quality and persistence of this
representation. It would also be instructive to investigate whether the formation of this map is affected by ‘remembered’ information from previous exposures to the environment, and whether this leads to problems when, for example, there are unanticipated changes to the environment. Investigation of these strategies using the same basic paradigm as was developed for the peripheral vision study (Chapter 4) would allow a direct comparison of the speed and accuracy of response allowed by each strategy. Additionally, expansions of the peripheral vision study which used higher perturbation magnitudes or different handhold sizes would allow the efficacy of reliance on peripheral vision to be investigated in greater detail.

In addition to further studies of healthy young adults’ balance recovery reactions, greater clinical and public health benefits are possible if the studies presented in this thesis and those suggested above are used to provide a baseline for the evaluation of the effects of aging, sensorimotor disorders, neurological disease and medication use, and as basis for the development and evaluation of clinical interventions. As was suggested in section 5.3, the extension of well-controlled studies of the efficacy of peripheral vision for guiding perturbation-evoked reach-to-grasp reactions to the older adult population has the potential to identify functional, but potentially reversible, age-related deficits in the ability to make use of information from the visual periphery. Likewise, the extension of the proposed studies of the formation and persistence of the visual-spatial ‘map’ to older adults could be used to investigate the effects of age-related declines in working spatial memory on balance recovery. In short, there is a substantial body of research still to be done in this area, the applications of which could contribute in meaningfully to the understanding of how reach-to-grasp balance recovery reactions are controlled, and to addressing the deficits which may lead to impaired visual control of balance-recovery reactions.

5.5 Conclusions

This thesis presents evidence that reach-to-grasp reactions can be controlled successfully when visual information is limited to either stored information from central vision, acquired prior to perturbation onset, or to continuously available peripheral vision of the grasp target. In fact, rather than having the eyes lead the hand, as is typical in voluntary limb movements, young adults choose to rely on stored central information and/or peripheral vision to guide compensatory reach-to-grasp balance recovery responses to unexpected loss of balance. Further
investigation of the efficacy of reliance on peripheral vision showed that peripheral vision can be used to guide perturbation-evoked reach-to-grasp reactions with similar accuracy to central vision. At moderate visual angles (20°-30°), the speed of response is also comparable to that achieved when continuous central vision is available; however, when the handhold is viewed at a higher visual angle (40°), there is a substantial reduction in the speed of the response (~75ms). An ongoing cognitive task was found to have little impact on either the speed or accuracy of the rapid reach-to-grasp reactions.
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Appendix I:

Determining the visual angle of objects in the visual field: an extended application of eye trackers

The appended paper was accepted as a short communication by the IEEE Transactions on Biomedical Engineering in August, 2008.
Determining the visual angle of objects in the visual field: an extended application of eye trackers

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Number of text pages and figures: 7 pages (7 pages max), 2 figures

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Acknowledgment: Supported by the Canadian Institutes of Health Research, Toronto Rehabilitation Institute, and University of Toronto (Vision Science Research Program, and Institute for Biomaterials and Biomedical Engineering).

Index Terms: eye movements, gaze behavior, central vision, peripheral vision, saccades, visual angles

© 2008 IEEE. Reprinted, with permission, from Scovil CY, King EC and Maki BE, Determining the visual angle of objects in the visual field: an extended application of eye trackers. IEEE Transactions on Biomedical Engineering (Accepted August 2008)
Abstract (50 words, max 50 for short communications)

Many eye-tracker systems display the point of central gaze fixation on video images of the viewed environment. We describe here a method for determining the visual angles of objects located in the periphery. Such data are needed to study the potential contributions of peripheral vision during cognitive and motor tasks.
I. Introduction

Eye trackers (ET’s) are commonly used to study gaze behavior in a wide range of research fields (e.g. visual-vestibular systems, visual attention, motor control) and activities (e.g. locomotion, sports, driving, reading) [1]. While some ET systems simply record eye movements, others display the point of gaze fixation on video images of the environment, as recorded by a head-mounted or remote “scene” camera [1]. Such systems allow the object that was fixated to be identified, but provide no quantitative information about the locations of objects in peripheral regions of the visual field.

The human eye focuses incoming light rays most accurately on the fovea, the retinal area of greatest visual acuity (visual angles <2.5°). The surrounding macula (visual angles <9°) also provides high acuity [2]. Although acuity decreases as the visual angle of the object moves farther into the periphery [2], studies have demonstrated that peripheral regions of the visual field do provide information that is important in many cognitive and motor tasks (e.g. spatial location [3-5] or detecting the movement of objects [6]). Typically, such findings have been derived from studies in which portions of the visual field are occluded (using special goggles, contact lenses or computer displays [5, 6]) or subjects are instructed to maintain fixation on a specified point [3, 4]. To study potential contributions of the central and peripheral visual fields under more natural task conditions, it is necessary to be able to determine the visual angles of various objects of interest over the duration of the cognitive or motor task being studied.

This communication presents a method for augmenting the point-of-gaze data provided from an ET by plotting associated visual-angle information on the scene-camera image, thus allowing the visual angles of objects of interest in the subject’s field of view to be determined. The method presented herein is valid for an ET system for which the spatial relationship between the eye and the ET remains constant. This could include a head-mounted ET on a mobile subject or an environment-mounted ET when the subject’s head is immobilized. Example data are presented, and the assumptions and sources of error are discussed.

II. Methods

The visual field of the eye may be thought of as a cone, of visual angle $\theta$, centered on the line of gaze (Fig. 1a). As a person views the surroundings, anything that falls within that cone
will be visible within the visual angle $\theta$. When using an ET, the three-dimensional scene viewed by the subject is recorded as a two-dimensional video image in the “image plane” of the ET scene camera. The ET calculates the intersection of the line of gaze with the image plane, and plots this “point of gaze”, $P$, on the recorded scene. To determine, with respect to $P$, the visual angle of objects in the scene, one must find the coordinates of the “gaze ellipse” created by the intersection of the visual-angle cone and the image plane.

**A. Derivation of Basic Method**

The fundamental objective is to convert distances recorded in the scene-camera image plane to visual angles, $\theta$, given the point of gaze, $P$, that is provided by the ET software (Fig. 1b). We define the point at which a perpendicular line of gaze would intersect the scene-camera image plane as $D$. Thus, the distance from any point of gaze to the perpendicular gaze point is $PD$. If the focal length of the scene-camera lens is $OD$ and gaze is inclined at angle $\alpha$, then:

$$\alpha = \tan^{-1}\left(\frac{PD}{OD}\right)$$  \hspace{1cm} (1)

If points A and C define the extents of the gaze ellipse, then:

$$AD = OD \cdot \tan(\alpha + \theta)$$  \hspace{1cm} (2)

$$CD = OD \cdot \tan(\alpha - \theta)$$  \hspace{1cm} (3)

and the length of the major axis of the ellipse, $AC$, can be calculated as:

$$AC = AD - CD$$  \hspace{1cm} (4)

This information then allows the location of the center of the ellipse, $B$, to be found using:

$$BD = CD + \frac{AC}{2}$$  \hspace{1cm} (5)

To fully describe the ellipse, the minor axis must also be determined. This is accomplished by finding the “equivalent circle” that results when the visual cone is intersected by a plane perpendicular to its axis, and passing through point B. This plane is represented by points E, B and F in Fig. 1b. The center of the equivalent circle, point E, is defined by:
\[ PE = BP \cdot \sin \alpha \]  \hspace{1cm} (6)

where \( BP = BD - PD \). The semi-minor axis of the gaze ellipse is defined by the radius, \( EF \), of the equivalent circle:

\[ EF = OE \cdot \tan \theta \]  \hspace{1cm} (7)

where \( OE = OP - PE = \frac{PD}{\sin \alpha} + BP \cdot \sin \alpha \). The gaze ellipse can now be defined in the scene-camera image plane using the coordinates of its center (point B) and the lengths of its semi-major (AB) and semi-minor (EF) axes:

\[
\frac{(x - B_x)^2}{AB^2} + \frac{(y - B_y)^2}{EF^2} = 1 \]  \hspace{1cm} (8)

The orientation of the ellipse within the scene-camera image plane (i.e. the angle between the ellipse axes and the x- and y-axes of the camera image) is defined by the orientation of PD.

**B. Calibration Procedure**

The above derivation defines the coordinates of the gaze ellipse in “real” units (e.g. mm); however, in order to plot the ellipse on the scene-camera image, it is necessary to express the equations in pixel units, which requires the scene-camera focal length \( OD \) to also be defined in pixel units. This can be accomplished by performing a simple calibration, which also serves to correct for any lens distortion. The calibration procedure involves fixing the scene camera perpendicular to a known grid (the “calibration plane” shown in Fig. 1), at a known distance \( OD' \), and then digitizing the location of the grid points in the recorded camera image in pixel units. For each grid point \( P' \), we know the values of \( P'D' \) and \( OD' \), and hence the corresponding angle \( \alpha \): \( \alpha = \tan^{-1}\left(\frac{P'D'}{OD'}\right) \). The effective value of \( OD \) (in pixel units) for each point \( P' \) in the calibration plane (and each corresponding point \( P \) in the digitized image) is then: \( OD = PD \cdot \cot(\alpha) \), or more directly:

\[ OD = PD \left( \frac{OD'}{P'D'} \right), \]  where PD is in pixel units. In allowing OD to vary according to the location of each calibration point, we correct for lens distortion. Interpolation can be used to estimate the value of OD for any points not explicitly digitized during the calibration.
C. Translation from Scene Camera to Eye’s Viewpoint

The above calculations define visual angles, with respect to the point of gaze, in the scene-camera image plane. Although the ET software correctly locates the point of gaze with respect to the scene-camera image, the scene-camera visual angles that we have calculated will differ from the corresponding visual angles of the eye because the lenses of the eye and the scene camera are not coincident (Fig. 1c). Fortunately, this error can be eliminated by measuring the offsets between the eye and the scene camera, and using these to adjust the angular coordinates of the points in the calibration plane.

If the calibration and scene-camera image planes are perpendicular to the subject’s perpendicular line of gaze (OD), points Oeye and Deye will be offset from points Ocam and Dcam by exactly the same distances in the calibration plane (Cx and Cy, Fig. 1c). Thus, the correction can be implemented by shifting point D’ in the calibration plane, using the formulae:

\[ D'_{\text{eye}, x} = D'_{\text{cam}, x} + C_x \]
\[ D'_{\text{eye}, y} = D'_{\text{cam}, y} + C_y \]

In addition, the perpendicular distance between the calibration plane and the observer must be adjusted to reflect the location of the eye rather than that of the camera:

\[ O_{\text{eye}}'D' = O_{\text{cam}}'D' + C_z \]

These changes will then alter the values of P'D' and OD' in the equations presented in Section II-B.

D. Collection of Example Experimental Data

Example data were collected, during ambulation, using a head-mounted ET (Model 501, Applied Sciences Laboratories, Bedford, MA) that determines gaze direction by using a miniature camera and infrared light source to record corneal reflections, and plots the point of gaze as a cursor on the image recorded by a miniature head-mounted scene camera. Several other types of ET are available, including those mounted on glasses or virtual reality goggles, or remote systems where the ET is attached to a surface such as a desk, computer monitor or vehicle dashboard [1]. As noted earlier, the equations in this paper are applicable to any system in which the head is fixed relative to the scene camera. Programs to implement the equations derived above were created using Matlab (Mathworks, Inc, Natik, MA).

III. Example Result
Fig. 2 displays a sample ET scene-camera image, with gaze ellipses plotted to indicate visual angles of 5°, 10°, 15°, 20° and 30° with respect to the point of gaze. While the subject’s gaze, in this example, was centered on the computer located on the desk, the gaze ellipses indicate the extent to which other objects of potential interest were visible within the central and peripheral visual fields. For example, the phone and the top of the chair were within a 10° visual angle, and the end of the handrail was within a 15° visual angle.

IV. Discussion

The method presented above involves a number of assumptions. These are listed below, along with a discussion of potential errors resulting from violation of each assumption.

A. Equipment characteristics

Assumption #A1: the location of the central gaze cursor, point P, is known exactly. All ET’s have some error in calculating the point of gaze, which is dependent on the design of the ET and the accuracy of the ET calibration. Uncertainty in the gaze location will propagate directly to the gaze-ellipse calculation. For example, an error of 0.5° in the ET system (a value commonly specified by ET manufacturers) would result in an uncertainty of ±0.5° in each visual-angle calculation.

Assumption #A2: the scene-camera lens has no distortion. Most lenses will introduce some distortion. Fortunately, however, this error is effectively eliminated by careful scene-camera calibration, using the procedures described in Section II-B. For our system, which uses an extreme wide-angle (“fish-eye”) lens in order to increase the camera’s field of view, we determined that failure to implement this correction would have caused errors of up to 30% in the visual angle (e.g. an error of ±3° for a visual angle of 10°).

B. Equipment set-up

Assumption #B1: the offset distances from the scene camera to the eye are fixed, and known. For our head-mounted system, we could measure these distances with 2mm accuracy in each direction. Numerical simulations indicate that this uncertainty results in very small (<0.1°) errors in the visual-angle calculations. Note that other minor violations of this assumption, such
as variation in the offset distances [e.g. due to slight (<1cm) slippage of a head-mounted ET],
would also cause comparatively small errors in visual angle calculations.

Assumption #B2: the scene-camera image plane is perpendicular to the subject’s ‘straight
ahead’ reference line of gaze. The locations of the gaze ellipses are calculated based on the gaze
inclination ($\alpha$) relative to a reference line of gaze (OD) that is assumed to be perpendicular to the
image and calibration planes (Fig. 1b). However, the orientation of the camera can be difficult to
adjust accurately, particularly in the case of a head-mounted ET system, where the scene camera
is very small. The error in gaze-ellipse determination due to error in scene-camera angle
increases with both gaze inclination, $\alpha$, and visual angle, $\theta$. For our equipment, scene-camera
alignment error was estimated to be $10^\circ$, and numerical simulations indicated that this would
result in errors of 10% to 20% in the visual angle.

Assumption #B3: the location of the perpendicular gaze point, D (Fig. 1), is known in
relation to the image coordinate system. For our setup, we adjusted the scene camera so that the
subject’s “straight ahead” gaze point was centered in the scene-camera image. We could achieve
this centering of point D to within 5% of the total image dimensions, which numerical
simulations indicated would result in an error of $\pm1^\circ$ in the visual-angle estimates.

In summary, provided that the scene-camera calibration is accurate, violation of
assumption #B2 is likely to have the greatest effect on the gaze-ellipse calculations. However,
the net effect of all of the assumptions must be considered. In our setup, numerical simulations
indicated that with careful calibration, measurement and setup of the ET system, we were able to
achieve total errors of $\pm1.5^\circ$ for a visual angle of $5^\circ$ and $\pm2.5^\circ$ for a visual angle of $20^\circ$. Thus,
reasonably accurate estimates of the visual angles of objects in the subject’s visual field are
achievable using the methods outlined in this paper. We anticipate that this extended application
of eye trackers will facilitate future research into the contributions of central and peripheral
vision to the control of cognitive and motor tasks and will assist in understanding the visual
information that people are able to gather from their surroundings.
References


Figure 1. Definition of the optics problem. Panel A illustrates how a given visual angle $\theta$ defines a cone centered about the line of gaze, which is inclined at angle $\alpha$. The intersection of this cone with the scene-camera image plane (i.e. the photosensor of the scene camera) defines the “gaze ellipse”. The location of the calibration plane, as defined in Section II-B, is also shown. An exaggerated two-dimensional representation of the above is shown in panel B, for purposes of illustrating the geometric calculations outlined in Equations 1-8. Point O is centered on the lens of the scene camera, P is the point of gaze determined by the ET software, and D is the point where the line of gaze would intersect the scene-camera image plane at a right angle. Points A and C denote the outer edges of the “gaze ellipse” (AC is the length of the major axis of the ellipse), B is the centre of the ellipse, and E is the centre of the “equivalent circle” (located in a plane perpendicular to the line of gaze), the radius of which (EF) defines the length of the semi-minor axis of the ellipse. Panel C illustrates (in two dimensions) how the calculations performed in relation to the calibration plane of the scene camera are adjusted to account for the offset between the camera and eye, represented by distances $C_x$ (not pictured), $C_y$ and $C_z$, and thereby correct the calculated visual angles so that they correspond to the visual field of the eye. The correspondence with the eye assumes that there are no significant refractive errors (e.g. due to severe myopia) or that such errors are corrected by lenses worn by the subject.
Figure 2. A sample ET scene camera image showing the point-of-gaze cursor (black square) determined by the ET software and the associated "gaze ellipses" that were determined using the method described in this paper. The plotted ellipses correspond to visual angles of 5°, 10°, 15°, 20° and 30°.