Postural Costs of Performing Cognitive Tasks

in

Non-Coincident Reference Frames

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Abbreviations

2-D	2-Dimensional
3-D	3-Dimensional
AP	Anterior-Posterior
COG	Centre of Gravity
COM	Centre of Mass
COP	Centre of Pressure
HMD	Head-Mounted Display
LTS	Long Time-Scale
ML	Medial-Lateral
RT	Response Time
STS	Short Time-Scale

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Declaration

All data collection and statistical analyses reported in this thesis are the work of the author. With minor exceptions, programming of the experiments and design of apparatus and data collection are the work of Dr Subhobrata Mitra, University of Warwick. Design of experiments, procedures and data analyses are the joint work of the author and Dr Subhobrata Mitra. All of the studies to this thesis were approved by Warwick University's Humanities and Social Sciences Research Ethics Committee.

Chapters 1 and 2 draw on material presented in Fraizer, E. V., & Mitra, Subhobrata, Methodological and interpretive issues in posture-cognition dual-tasking in upright stance, *Gait & Posture* (in press).

Chapters 3 and 4 draw on material presented in Mitra, Subhobrata., & Fraizer, E. V. (2004), Effects of explicit sway minimization on postural-suprapostural dual-tasking, *Human Movement Science, 23*, 1-20.

Chapters 1-3, 5-6, and 8 draw on material submitted for publication, Fraizer, E. V., & Mitra, Subhobrata. Postural costs of performing cognitive tasks in non-coincident reference frames, *Experimental Brain Research* (under review).

In all other respects, material presented in this thesis is the work of the author, and has not been previously presented for a degree or similar purpose.

Foreword and Summary

An extensive literature exists attesting to the limited-capacity performance of everyday tasks, such as looking and mental manipulation. Only relatively recently has empirical interest turned towards the capacity limitations of the body coordinations (such as posture control) that provide the physical substrate for cognitive operations (and so mandatorily coexist with cognition). What are the capacity implications for the body's safety and mobility, for example, in accommodating the need to stabilize the eye-head apparatus for looking, or when mentally manipulating objects in 3-D space? Specifically, what are the postural costs in having to position and orientate the body in its own task space while supporting spatial operations in cognitive task space? What are the performance implications, in turn, for everyday cognitive tasks when posture control is challenged in this way? The purpose of this thesis was to establish a theoretical and methodological basis for examining any postural costs that may arise from the sharing or partitioning of spatial reference frames between these two components (a *frame co-registration cost hypothesis*).

In 7 experiments, young adults performed either conjunction visual search or mental rotation tasks (cognitive component) while standing upright (postural component). Visual search probed cognitive operations in extrapersonal space and mental rotation probed operations in representational space. Immersive visualization was used to operationalise postural and cognitive task contexts, by arranging for the two tasks (under varying postural and cognitive task-load conditions) to be carried out with respect to two spatial reference frames that were either coincident or non-coincident with each other. Aside from the expected performance trade-offs due to task-load manipulations, non-coincidence of reference frames was found to significantly add to postural costs for cognitive operations in extrapersonal space (visual search) and for representational space (mental rotation).

These results demonstrate that the maintenance of multiple task-spaces can be a source of interference in posture-cognition dual-tasking. Such interference may arise, it is suggested, from the dynamics of time-sharing between underlying spatial coordinations required for these tasks. Beyond its importance within embodied cognition research, this work may have theoretical and methodological relevance to the study of posture-cognition in the elderly, and to the study of balance and coordination problems in learning difficulties such as those encountered in dyslexia and the autistic spectrum.

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Chapter 1

Introduction

1.1 Embodied attention

The ability to control, maintain and rapidly reorganize body posture and spatial orientation is fundamental to the adaptive success of nearly all animal species, including humans [28]. The large-scale perceptual and neuromuscular coordinations that underpin such activities as standing, leaning, orienting and recovering balance are complex, but our usual experience of performing them effortlessly contrasts markedly with the effort and capacity limitations traditionally associated with many, arguably simpler, cognitive tasks, such as looking, listening and thinking. This may have underpinned the historical view that postural coordinations are perhaps different sorts of tasks to cognitive ones [150].

Over recent decades, however, research has started to highlight the fallacy of this historical separation between studies of cognition and coordination. Firstly, research within developmental psychology has demonstrated the crucial impact of motor skills on the development of perception [44], spatial orientation [3; 29; 30], social interaction [94] and memory [226]. Second, the research traditions that are now collectively referred to as embodied cognition [52; 89; 112] have emphasised how the evolutionary origin of the nervous system as a control system for the body must affect the architecture and performance of purportedly ‘central’ cognitive functions. Not only are many cognitive operations in daily life heavily reliant upon ongoing perceptual evaluation and motor manipulation [19; 20; 50], even our offline memory, reasoning and problem-solving operations are said to depend upon sensorimotor simulations of real or imagined events ([68; 89; 91; 92; 112; 277]; see also [112; 124; 125], for the bodily basis of logic, inference and abstract meaning).

Additional evidence that perceptual-cognitive processes are inextricably tied-up with coordination skills comes from a growing volume of work on shared attentional processes in postural and cognitive tasks. Drawing on dual-task methodology from cognitive psychology, these investigations are showing that even highly practised coordinations such as standing and locomotion engage the same cognitive resources as attentive cognitive tasks, and when these are performed concurrently, negative patterns of processing interference between the tasks can be detected to varying degrees in young and old, healthy and clinical populations (see [286], for a review). Thus, performing a cognitive task during mechanically unperturbed standing is frequently shown to result in increased amount or variability of postural sway [107; 146; 162; 235]—a result commonly interpreted as indicating decreased postural stability. A complementary finding is that simple adjustments to standing balance can adversely affect performance on cognitive tasks [116; 162]. To this effect, posture control is ‘cognitively penetrable’ [250]. This represents an important theoretical shift, but it would also appear to be a matter of substantial clinical interest given that (a) concurrent cognitive activity is shown to affect postural destabilization and falling in the elderly (see [131], for a review), and (b) learning difficulties such as dyslexia [181] and the autistic spectrum [174], though defined by higher level cognitive difficulties, are accompanied by a variety of coordination difficulties.

The relationship between postural control and higher level cognition is not straightforward, however. Many dual-task studies have shown decreased sway for a concurrent cognitive task during unperturbed standing [63; 70; 106; 272], while others have failed to find postural control effects [116; 250; 294]. Although there are considerable methodological differences between studies in terms of test populations, sway variables and dual-tasks, no systematic pattern of results emerges from the literature that would fully explain differences in postural responses under dual-task conditions. This underscores the fact that the specific mechanisms underling interference in posture-cognition dual-tasking are only poorly understood.

The most common indication from the dual-task research is that processing interference in cognition-coordinations occurs because these tasks compete for shared spatial processing resources [116; 150], or because dual-tasking challenges the online sensorimotor mechanisms required for postural control [212; 250]. Reaching beyond these general terms accounts, this thesis considers an important and as yet poorly understood aspect of sharing spatial and temporal operations between cognition and posture control—the impact of having to calibrate and perform these tasks with respect to two non-coincident reference frames. A fundamental consideration in this regard is that in everyday life every instance of cognitive activity occurs within the context of one or more large-scale, mandatory motor coordinations governing balance, locomotion and spatial orientation of the body. The organization of these coordinations is strictly constrained by the need to physically act and react with respect to a gravitational-inertial world frame. A concurrent cognitive task, however, can have parsimonious, performance-critical description in one of a number of reference frames [46; 87; 132], and which can have complex (frame) dynamics relative to the postural world frame. In this sense, how effortlessly a concurrent cognitive task coexists with posture control may depend not just on each task's component load and resulting draw on common information-processing capacities, but also their deployment in terms of how tightly the cognitive task context or *task space* can be embedded within the behavioural context provided by posture control.

1.2 Aim and outline of the thesis: Postural costs of performing cognitive tasks in non-coincident reference frames

The aim of the thesis was to provide a theoretical and methodological platform for the investigation of postural costs of maintaining stable cognitive task spaces in posture-cognition dual-tasking. Immersive visualization (head-mounted display and motion-tracking) was used to operationalise postural and cognitive task contexts by arranging for the two tasks to be carried out with respect to two spatial reference frames that were either coincident or non-coincident with each other. To investigate any interactions between frame coincidence or non-coincidence and task-load, the postural component's task-load was manipulated by requiring participants to stand in either open (ankles about 10 cm apart and feet at comfortable angle) or closed stance (feet flush against each other). Closed stance reduces the support base area, and increases the difficulty of maintaining balance. Cognitive task-load was manipulated by varying the number of distractors for a conjunction search task, or else varying the size of the displacement angle for a mental rotation task. To anticipate the concluding chapter, if the behavioural flexibility and adaptive advantages of freeing cognitive task spaces from strict alignment with postural or locomotor control spaces comes at the expense of relentless contention scheduling between postural and cognitive task spaces (a *frame co-registration cost hypothesis*), there may be important implications for our understanding of postural vulnerability among the elderly as well as for emerging links between cognitive disabilities and coordination deficits.

The theoretical and methodological framework to the thesis is developed in *Chapter 2*. The opening literature review discusses methods for the assessment and measurement of postural control, and introduces a key conceptual issue concerning interpretations given to postural sway (see below). In a second literature review, the dual-task data that has demonstrated the existence of interference between posture-cognition tasks is summarized and then discussed in terms of the general theoretical frameworks that attempt to contain the data. The theoretical framework and experimental outline to the thesis are presented in the third part of the chapter. Methodology to the thesis experiments is given in *Chapter 3*.

A key issue to emerge from the posture control literature is that postural sway cannot be assumed always as autonomously and automatically directed at the control of balance, but may instead reflect the modulating use of sway in support of the suprapostural (i.e., coordination-based) task. The theoretical implication, exposed in the posture-cognition literature review, is that increased sway cannot be reliably interpreted as signalling increased mechanical destabilization. Rigorous investigation of the frame co-registration cost hypothesis therefore required a means of disambiguating the experimental data arising from participants' use of sway. An attentional priority paradigm in which young adults were required to minimize their sway while focussing on a conjunction visual search task was successfully devised for this purpose (Experiment 1), and this is developed in *Chapter 4*.

The principal investigative work of the thesis begins in *Chapter 5*. In two experiments, dual-task performance in young adults was compared for a conjunction visual search task presented in spatial reference frames that either coincided, or did not. Aside from expected performance trade-offs due to task-load manipulations, non-coincidence of reference frames led to performance decrements in the postural task. This pattern persisted across instructions prioritising search only (Experiment

2) or specifying deliberate sway minimization as well (Experiment 3). These results provided first evidence that task-linked reference frames add postural costs to posture-cognition dual-tasking.

In *Chapter 6*, the co-registration hypothesis is defended against possible objection that posture-relevant visual information in coincident frames could be used to advantage postural performance in that condition, as compared to performance in the non-coincident frames condition. In two experiments (Experiments 4 and 5), cognitive penetrability of posture control in young adults was observed when visual search was split between coincident and non-coincident frames and when frame conditions were rendered identical in visual information relevant to posture control. In a further experiment (Experiment 6), the applicability of the thesis visual search paradigm to the more general experimental case of posture-cognition dual-tasking was demonstrated by showing that visual search in 3-D in immersive environments has no more measurable impact on postural control than search in 2-D.

In *Chapter 7*, the frame co-registration cost hypothesis is extended to the sphere of representational space. Dual-task performance in young adults was compared for a mental rotation task presented in either coincident or non-coincident spatial reference frames (Experiment 7). Robust effects of frame non-coincidence on postural sway were detected, confirming the importance of the frame co-registration cost hypothesis for concurrent activities involving postural control and internally generated and maintained representations for the cognitive task.

In *Chapter 8*, the thesis findings are discussed with respect to the posture-cognition dual-task literature, and broader implications of the thesis are drawn out.

Chapter 2

Theoretical and Methodological Context, and Thesis Framework

2.1 Introduction

The theoretical and methodological context of the thesis is presented in two parts. Following an introduction to the organization and mechanisms of posture control, the first part of the chapter discusses conceptual and methodological issues relating to the assessment and measurement of human balance. The second part of the chapter presents methodological and interpretive issues in posture-cognition dual-tasking during upright. The posture-cognition dual-task data is summarized, and the data discussed in terms of the most commonly applied theoretical frameworks. Finally, the theoretical framework, experimental outline and main experimental prediction to the thesis are presented.

2.2 Posture control

The goal of posture control is to preserve posture (the bodies' geometric linkages) against gravity while providing a reference frame for perception and action with respect to the world ([147], for a review). The particular orientating posture can depend on the reference task. During complex motor tasks, for example, most animals, including humans, tend to control trunk and head movements in order to stabilize the orientation of the gravitoinertial apparatus (vestibular system) and the eye-head system in space [10; 202], thereby simplifying the processing of sensory feedback [101].

Postural orientation is integral to posture equilibrium or balance, the preservation of the body's centre of mass (COM) with respect to the ground [147].[1] The need to maintain a high COM over a relatively small base of support means that bipedal upright stance is inherently unstable. Any angular displacement of the body's COM (as normally results from a change in posture) precipitates a gravity-induced torque at the support surface that disturbs the equilibrium position. Compensating for this gravitational-inertial effect on the body's segments requires re-adjustment of the body's posture and the application of corrective torques to the support base, such that the body's line of gravity (i.e., the line that runs through the body's COM, in the direction of gravity) once more projects over the support surface [161; 199].[2]

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[1] The terms "postural control" and "balance control" are used interchangeably in the posture-cognition literature when referring to regulation of the body's position, and this thesis follows in this convention.

[2] The degree to which the body is being kept within equilibrium limits (i.e., the extent to which the line of gravity falls within the base of support) is commonly referred to as postural stability (see, e.g., [236]). Other researchers have used this term to refer to the state in which uncontrolled movements of the body are minimized for purposes of perception and action (see, e.g., [215]). The latter position is discussed in sections 2.2.2 and 2.3.2.

The ability to maintain the body's COM within equilibrium bounds is often approximated as a multisegmental inverted pendulum problem, involving weighted displacement of proximal (e.g., trunk) and distal (e.g., ankle) joints over the support base [84; 86; 280]. Muscles and ligaments spanning the joints act as stabilizing elements by providing instantaneous torque due to muscle viscosity, mechanical stiffness and damping (length-force tensions) [32]. Aside contributions from spinally-mediated reflexes (e.g., stretch reflexes), resistances to self-generated and externally-imposed perturbations are thought to involve functionally organized collectives of joints and muscles that simplify the actor's choice over the system's many degrees of freedom [28; 261].

The precise pattern of muscle activation, joint movement and ground reaction force depends on sensory and environmental factors; for instance, perturbation magnitude in different sensory environments and balance goal, as well as biomechanical factors such as body and surface configuration (see [100; 101], for reviews). Against small external perturbations on a firm support base, for example, humans often behave as a single-link inverted pendulum, stabilizing themselves against the disturbance by applying torque to the ankles, with little hip flexion [170]. The resulting distal-to-proximal pattern of muscle activation can be compared to the early activation of trunk and hip muscles occurring for larger disturbances or with a smaller supporting area, when the body's COM is near equilibrium limits [187]. In the latter situation, most humans stabilize themselves by using the inertia of their body segments and their mechanical coupling, involving movement of the trunk around the hip joint

[102; 172]. Stronger disturbances may call for coordinated ankle and hip displacements of the body's COM over the support base [102; 172], while a change in base is observed to invoke a stepping strategy [138; 139].

A well-established view is that these postural and movement patterns occur as locally constrained but centrally selected motor programs, controlled by high-level neurocognitive strategies, and implemented by feedback processes that signal deviations from a unique postural set-point ([18]; see also [99]). Other work in postural control dynamics has suggested that these apparently local constraints may in fact occur as spontaneous, higher-level pattern formations. Studies involving standing and visual tracking [22; 144; 239], as well as steady-state standing in the context of gravity (so-called 'quiet standing') [60], have shown that the human body spontaneously adopts two co-existing modes of movement during upright standing, rather than a continuum of mixed strategies [60]. These consist of an in-phase mode, with the ankle-hip joints moving simultaneously in the same direction, and an anti-phase mode, with the two joints oscillating simultaneously in opposite directions, one-mode predominating depending on sensory, environmental and intentional (emotional-cognitive) conditions [22].

The postural stabilization process is thought to involve forward motor commands directed at the expected equilibrium disturbance [84; 86; 168; 265], as well as reactive control based on sensorimotor inputs [187; 199]. Studies suggest that some combination of the respective feedforward and feedback mechanisms might represent different control systems—one subsystem for determining the internal reference point to which the equilibrium is maintained, and a second control directed at maintaining equilibrium about the target reference point [300]. In one interpretation, feedforward control operates cognitively long term to stabilize an unstable, reactive mechanical system by pushing the neuromuscular system back towards its reference point ([21]; see also [86]). A second view, which similarly identifies two-part behaviour but with different conclusions, is that persistent migrations from the equilibrium position over short time intervals are corrected by an anti-persistent, feedback loop operating at longer time-scale (>1 s) once departures exceed a threshold magnitude [53]. The presence of open- and closed-loop controls has been interpreted as the use of exploratory sway as source of information in the detection of stability boundaries [214] followed by corrective activity ([221]; see [86; 300], for similar considerations).

2.2.1 Balance assessment and measures

Various techniques have been used to capture and quantify the small, low-amplitude motions of the body that accompany spontaneous, mechanically unperturbed upright standing, and the larger amplitude motions that result from mechanically or perceptually perturbed stance. Most usually, data is recorded using transducer force platforms taking the vertical ground reaction forces at the point of application (the centre of pressure, COP) along anterior-posterior and medial-lateral axes. However, since COP is a measure of the error signal underlying the centre of mass (COM) position, studies reporting COP actually provide overestimates of centre of gravity excursions [21; 118; 279]. An alternative means of quantifying sway is to use mechanical or electromagnetic devices to directly record COM motions from body segments such as the head or hip [2; 67; 126; 135; 162; 222] .

The most commonly used sway measures are parameter estimates of the COP or COM trajectory, derived from signal analysis, and presented in time or frequency domains ([204], for a review).[3] The large (often redundant) number of available statistical parameters can considerably complicate data interpretation [178; 223], although several studies have recommended particular summary measures based on their sensitivity in capturing individual differences [105; 136; 204; 211] or in describing particular characteristics of sway [223]. For example, in the frequency domain, spectral analysis has been used to identify postural constraints in terms of time-dependent postural behaviour [48; 63; 65; 157]. In the time domain, velocity-related measures (e.g., sway path length) have been reported as discriminating between decreased balance control and random postural activity better than displacement-related measures ([196]; see [148]). On the other hand, displacement

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[3] The electrical signal taken (transduced) from a COP or COM displacement can be analysed in terms of change in a parameter estimate over time, or in terms of both time and frequency. The latter analysis includes methods such as Fast Fourier Transformation or spectral analysis, and which are used to separate the large sine wave and significant other sine wave components found for the time domain. Typically, the aim is to match frequency width and average signal power to particular physiological characteristics of the system, or to uncover differences in system behaviour between subject populations.

measures (e.g., standard deviation) take on greater significance when comparing sway performances in different age groups, especially under perturbed stance conditions [211]. There remains no agreement, however, as to which summary statistic best describes postural stability. More pertinently, it is not clear from the posture-cognition dual-task data (reviewed in section 2.3) how the different measures that have been used may relate to each other in the context of posture-cognition dual-task performance (there being no discernable pattern between measures, dual-task types, and dual-task outcomes).

A related concern is that, while the reliability of signal recording increases with sampling duration [48; 74], the validity of signal analysis is compromised by the assumption that sway values are stationary over the length of posture trial periods. As earlier discussed, work in stochastic processes [49; 53; 54; 178] has shown that posture sway during standing is a bounded random walk, meaning that the mean position of sway can drift over time. As a result, a posture trial may contain both shorter and longer time-scale motions, with the system exerting tighter or looser control over different time-scales, depending on the precise posture-cognition dual-task and task load conditions. Under a low cognitive-load situation, for example, the system may be able to exercise strict control over longer time-scale motions, whereas a diversion of resources into cognitive task performance may slow the rate of postural corrections, resulting in reduced frequency of sway. Equally possible, when few attentional resources are required the system may be free to drift or ‘ramble’ [299] to a greater degree than under conditions of increased cognitive task difficulty [106].

Attempts have been made to capture the dynamic organization of postural behaviour during dual-tasking using non-linear techniques [198; 208; 218; 220; 224]. As mentioned however, time series such as COP appear not to have much low dimensional dynamics, being best described as a random walk [49; 53; 54; 178]. This means that postural organizations may be rather general and without a low level deterministic structure [219]. A simplified means developed to account for non-linear time-dependent behaviour is to compute shorter and longer time-scale motions from the moving windowed signal. Computing the COM (or COP) mean standard deviation over a series of non-overlapping data windows for each posture trial [157; 222] gives a measure of shorter time-scale activity [162]. The root mean square distance between the windowed mean standard deviations gives a measure of longer-time scale activity (see Chapter 3, section 3.2.4, for further details and discussion of these measures). Together, the two measures allow for a minimally multi-resolution view of sway patterns, while at same time ensuring a degree of consistency with the standard measures from posture-cognition dual-task studies [162].

2.2.2 Visual information in postural control

Postural control involves the dynamic regulation and integration of visual, vestibular and somatosensory (cutaneous and proprioceptive) inputs (see [111; 160; 199], for reviews). Against external perturbations on firm ground, somatosensory information tends to play a dominant role in upright postural control [103; 104; 110; 161]. Where somatosensory information is limited by a reduced base of support, however, vestibular and visual information have increased importance ([59]; see [42; 171]).

With respect to visual information, the low-frequency and low-amplitude oscillatory displacements of the body (chiefly in the AP direction) characteristic of spontaneous sway give rise to dynamic changes to optic flow (i.e., changes in the angular positions of points in the visual environment). Small displacements of the visual environment (as little as 2.5 cm for a viewing distance of 2 m, [244], below the threshold for conscious perception) are sufficient to induce postural sway [72]. Physical displacement of the visible surroundings using moving room environments [128; 186; 243; 244] or simulated displacement using computer-generated videographic displays [23; 72; 262; 269] are found to induce sway, while stationary visual environments tend to attenuate postural sway. Sinusoidal movement of the visible surround produces a matching sinusoidal postural response [72; 128; 229; 263; 264], and the temporal coupling between stimulus and sway found to be controlled or influenced by such factors as motion parallax [38; 93], and image velocity [129], size and expansion ([127], but see [72]).

With visual motion in the frontal or sideways plane, body sway shows a phase lead at low visual frequencies and a phase lag at higher frequencies [129]. This suggests an ability to track (or anticipate) visual field motion, so as to minimize the amount of relative displacement between the body and the environment [101]. In one interpretation, posture is then stabilized with respect to a minimum detection threshold by minimizing retinal slip (i.e., movement of the retina relative to the optical projection of the object) [128]. These apparently automatic endeavours to control optic flow through minimizing the body's motions are generally interpreted as attempts to secure or increase stance stability [162]. In this so-called autonomous control view of posture control [162; 245; 246], reducing or controlling the level of sway is seen as a reflexive goal of the posture system, and any increase in the level of sway interpreted as a weakening of the level of control.

An alternative framework is provided by the facilitatory control view [245; 246], which stresses that in most everyday situations (but not often in experiments using the quiet stance paradigm, as above), posture control functions primarily as an enabler or facilitator of suprapostural activities [215]. Beyond the basic requirement of keeping the COM well within the stability boundary, posture control's facilitatory functions may or may not warrant further sway minimization. Thus, in situations where there are no imminent threats to body safety and where there are ongoing suprapostural tasks, sway may increase or decrease depending on the suprapostural task requirements. Sway may increase, for example, when a visual suprapostural task benefits from larger excursions of the viewpoint (e.g., spotting partially occluded objects), and similarly, decrease when the task requires very precise eye fixations, as perhaps, for a visual search task [245; 246].

Since the postural task employed in this thesis offered no extreme threat to stance stability, a facilitatory control view has the consequence that participants might have attempted to strategically control or intentionally modulate sway in support of the cognitive (suprapostural) task, rather than choose to direct resources more fully to controlling balance. Under these circumstances, increased sway for any particular reference frame (or task-load) setting could not be specifically interpreted as a resource draw into attempted sway control activities, as opposed, say, to a relative neglect of the level of sway in favour of the cognitive task. To de-confound these two explanations of sway patterns, the visual search task paradigm for the thesis incorporated control experiments that required participants to actively minimize their sway while performing the visual search task (see Chapters 4-6, in detail).

Historically, greater sensitivity to motion perception has been demonstrated for the peripheral retina, used for coding the speed and direction, over central vision (approximately 30 degrees of the visual field, [24]), used mainly for discriminating position signals and stable characteristics of the environment [26]. Peripheral vision is very sensitive to lamellar optical flow and, given that the ground surface is an essential frame of reference in everyday life, expectedly found to strongly affect both stability and balance [129; 243]. In context of the immersive environment (head-mounted display and motion-tracking) employed in the thesis paradigm however, it is germane to note that both radial and lamellar flow as small as 15 degrees in diameter at the fovea region are found to induce postural sway [13; 183]. As noted in the literature [162; 290], a perhaps more important issue in using head-mounted displays (HMDs) concerns the latency involved both in tracking and generating a new image. Tracking latency and frame rate as small as 15 ms can be detected by the human viewer [4].[4] Where the delay between the user's actions and the displayed response is large enough [73], or time on task long enough [176; 166] or task complexity [188] great enough, cue conflict between competing visual and vestibular signals may give rise to motion sickness in susceptible individuals. The paradigm type employed in this thesis, however, involved short exposure duration and induced only small amplitude body sway, and so is unlikely to have had significantly disruptive effect on participants' sensorimotor function.[5] Concerning visual task performance, prolonged HMD use (> 10 min) may cause binocular function defects ([165; 166] but see [228]), and both frame rate and latency have been found to significantly affect perceptual stability and performance for a tracking task [78]. In respect of the cognitive tasks employed in the present work, however, direct comparison of visual search performances in HMDs and traditional screen

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[4] Note. For a frame rate kept constant and predictable, as for the apparatus used in this thesis (see section 3.2.1, for details), latency rate depends only on the sampling and processing time between the actor's action and the displayed response.

[5] Of the about 200 participants to the thesis experiments (including pilot work), four people complained of motion discomfort. In each case, the session was immediately terminated by the experimenter.

interfaces has shown the former search to be more efficient [195], while work on mental rotation has shown object-matching in immersive environments to be as effective (but not as efficient) as in real-world environments [227; 276].

2.3 Posture-cognition dual-tasking

Physiological [85; 99; 102] and neurocognitive [206; 207] investigations show that efforts to regain and maintain posture against external perturbations are demanding of the same sorts of cognitive processes used to perform mentally effortful tasks. Supporting evidence that cognition has a role in posture control comes from behavioural studies examining reciprocal modulating effects of concurrent postural and cognitive activities. Drawing on dual-task methodology from cognitive psychology, these investigations are showing with some consistency that cognitive task performance is detrimentally affected when stance is mechanically or visually perturbed [14; 15; 36; 40; 210; 212; 213; 234; 250; 294]. This cognitive dual-task decrement is particularly pronounced in older [36; 40; 210; 234; 250] and balance-impaired adults [36; 210; 213; 234], as compared to performances in young adults and controls, reflecting presumably the lesser psychomotor capacity of the elderly and infirm to contain the effects of a postural challenge. On the postural performance side, secondary task manipulations during perturbed standing are often found to promote increased amount or variability of postural sway [15; 36; 146; 157; 197; 198; 210; 212; 213; 234; 235]—a result commonly interpreted as indicating decreased postural stability. This effect is greater or more common in older adults and patients [36; 210; 212; 234; 235], and indeed a number of studies have reported reduced sway in healthy young adults for a concurrent cognitive activity performed under perturbed stance dual-task conditions [14; 36; 64; 65; 217; 218].

Cognitive-task decrements are also found for concurrent tasks performed in unperturbed stance, although this rarer result tends to occur only when posture control is excessively challenged by reductions in the support base, such as in feet-together standing [162] or standing with feet lined up heel-to-toe [116]. On the postural side, secondary task manipulations have produced a mixed set of results, variously bringing about increased [107; 137; 142; 146; 159; 162; 210; 235] or decreased postural sway [237; 63-65; 70; 106; 218, Exp 2; 268; 272], or else leaving sway unchanged [116; 250; 267; 294]. In line with the data for perturbed stance, postural dual-task decrements during unperturbed standing tend to be greater or more common in older adults [62; 107; 151; 210] and patients [96; 142; 143; 210] than young adults and controls. However, for a range of postural conditions, decreased sway in older adult and clinical groups during dual-tasking is not unknown [15; 41; 70; 159; 248; 272], and several studies have reported reduced sway in older but not younger adults under dual-task conditions that threatened [41] or especially taxed [159; 248] posture control (but see [107]).

In summary, having to maintain upright stance under conditions that substantially challenge balance is often found to affect cognitive task performance. Less reliable are the ways in which concurrent cognitive tasks impact on postural performance.

While the ability in older and balance-impaired adults to maintain and regain balance under dual-tasking conditions appears to be hampered by the execution of a concurrent cognitive task, secondary task manipulations have produced a more varied set of results in young adults. In particular, the diverse data on posture-cognition dual-tasking in the perhaps more ecologically valid and common case of unperturbed stance presents a challenge to discovering and understanding the precise cognitive task conditions that affect postural control. One complicating factor in cross-study comparisons of dual-tasking concerns problematic issues arising from the importing of psychological research into the study of posture-cognition. This issue is next discussed.

2.3.1 Dual-task methodology in posture-cognition studies

Efforts to impose a theoretical structure on posture-cognition outcomes have mostly mirrored two broad (but not necessarily mutually exclusive [133; 173]) frameworks used in cognitive psychology to explain dual-task decrements. Capacity theory, on the one hand, views dual-task interference as arising from the parallel sharing of a limited set of general-purpose resources [113] or specialized structures [274; 275]. On this account, when combined task demands exceed (centralized or particular) resource supply, degraded performance is observed on one task, or both. Bottleneck accounts, in contrast, emphasize the serial (i.e., sequential) nature of the dual-task process, in terms of the single-channel filtering or scheduling of information at stimulus encoding [273], identification [69] or decision-response stages [193]. When such sources of interference occur, the nervous system is said to temporarily postpone (i.e., time-share) operations on one task in favour of operations on the prioritized task, resulting in reduced performance on the non-priority task.

When testing for dual-task interference, the most common approach (in general, as well as in posture-cognition research) is to compare dual-task performance in both tasks against their baseline performance, and to probe for interference by examining interactions between dual-task components (see [184], for a discussion on candidate scores for dual-tasks). As has been noted in the literature [286], dual-task interactions cannot be used to infer the absolute attentional cost associated with postural control [1; 83; 90]—a point implicitly or explicitly acknowledged in the few studies that have attempted general-purpose resource explanations of interference based on task interactions [64; 213; 294]. Also, dual-task interactions provide only limited means of discriminating between general-capacity and specialized capacity or bottleneck accounts of task interference [1]. The interpretation of such interactions can be more reliable, however, in the context of methodology that incorporates task difficulty and priority manipulations ([33]; see [90]), tracking tasks [140; 182], catch trials [123; 146] or the selective application of tasks that tap similar resource pools [146]. These cautionary caveats aside, a widely held view is that the controlled interplay of postural and secondary tasks can be used to understand the nature of competing task demands, if not their precise shared attentional demand or dynamics.

As mentioned, the transfer of dual-task methodology to the posture-cognition setting has usually involved so-called single- to dual-task performance comparisons in which dual-task effects are measured against the ‘isolated’ performance of the baseline task [14]. Implicit in this approach is the assumption that when subjects are asked to perform a postural task such as standing upright, but are given no instructions to perform a specific cognitive task, the only task-load they carry is of the postural task. This assumption is clearly problematic because experimenters have no control over what subjects think about in such baseline conditions. Adding instructions to perform an explicit (i.e., experimenter-specified) cognitive task alongside a balancing task does not simply add a cognitive task where there was none. It actually replaces an unspecified cognitive task of unknown load, with a specified task of known load. Performance differences can be therefore expected between the two dual-task settings irrespective of the load that each task component brings to the dual-task situation.

The use of baselines is further problematic because the common requirement to stand as still as possible during the baseline recording period could encourage subjects to ‘concentrate’ on the balancing task in a manner that negatively interferes with the automatic processes underlying postural control [106; 268]. Support for this view comes from the earliest of posture-cognition studies in which Fearing [82] showed that the release of attention away from balance control and towards a secondary task can enhance postural stability. This outcome was accredited to a reduction in balance anxiety following the switching of attention to the secondary task [82]. The theme of facilitating balance by external focus has been examined in a series of studies that show increased postural stability when subjects adopt an external focus on the postural task (i.e., focus on the *consequences* of the postural task) relative to an internal focus (i.e., focus *on* the postural task) [157; 291; 292]; see Chapter 4, for further discussion). One suggestion from the work is that the attentional load associated with the postural task in the baseline condition can differ markedly to that in the dual-task condition, irrespective of secondary task load. A second outcome of the work is to illustrate the important role of instruction in the dual-task emphasis that subjects are asked to bring to the experimental situation. Despite the existing appreciation in the literature that a change in attentional priority in one or other dual-task component can bias the allocation of resources [130; 235], posture-cognition studies have seldom raised the issue of the instruction set's effects, or considered which other studies are, in this sense, comparable.

Baseline versus dual-task comparisons carry the additional concern that physically responding to secondary tasks (for example, verbal answers or button pressing) may generate mechanical demands that produce changes in sway that do not have to do with cognitive load [65; 217; 218; 272; 296]. For this reason, it has been argued that paradigms incorporating baseline conditions should be limited to delayed response actions that come strictly after posture data collection ends [217; 218]. This would of course limit any such paradigm to studying or involving working memory retention periods only. An alternative is to devise baseline trials that require the same physical response as the experimental dual-task condition but which do not carry the task load associated with the explicit cognitive task (see, e.g., [238]). Concerns stemming from the use of baselines can be altogether avoided, however, by restricting performance comparisons to manipulations of task difficulty under explicit dual-task conditions. Ideal in this respect are tasks whose load can be directly quantified, scaled by experimental manipulations, and confirmed from subjects' performance, such as the visual search and mental rotation tasks employed in this thesis (see also, [162]).

2.3.2 The nature of interference in posture-cognition dual-tasks

As previously mentioned, the most commonly used explanation for posture-cognition dual-task interference is that these tasks compete in parallel for one or more pool of resources, or else serially engage common input/output or response mechanisms. Methodological hurdles notwithstanding, a general-purpose resource model of the data is severely compromised by the fact that reductions in postural sway can be obtained without graded degradation in the cognitive task [65; 106; 248; 272]. Instead, the literature has tended to gravitate towards interference accounts that implicate competition for specialized resource pools (e.g., spatial resources [116; 150]), or bottlenecks in response processes [212; 234; 251; 252] or motor mechanisms [65; 296].

Early investigations into interference in cognition-coordinations in the context of aging demonstrated that, beyond performance degradation due to reduced peripheral sensorimotor function [141; 287], an important cause of decreased stability in the aged is a slowing of the online sensorimotor mechanisms required for sensory integration [240; 241; 247]. For instance, the elderly are less able to modulate their sway in response to perturbations that involve the transitional loss and return of vision, as compared to their younger counterparts [250]. In particular, it has been suggested that sensory conflict situations requiring the effortful integration and resolution of sensory inputs have their impact on postural control by slowing the informational update rate in the postural orientation process ([213]; see also, [249; 295]). Although a theoretical basis to time-sharing between cognition and coordinations has yet to be fully cached out, work on the temporal characteristics of posture control in dual-task contexts would suggest that the updating process in turn impacts on cognitive task performance. For example, disruption to a continuous visuomotor task is shown to be associated with the attentionally-demanding phase of stance recovery (about 350 ms after the onset of the balance reaction) but not with the reflexive initiation phase of the balancing activity ([182]; see [154], for a similar, seated postural activity, and [140], for individual differences in adaptive switching of attention between balance and a continuous visuomotor tracking task).

Cognitive processes that underpin online sensorimotor adjustments in the balance control process are thought to involve feedforward representations [84; 86; 168; 265] as well as reactive control of sensorimotor inputs [187; 199]. While it is not known whether attentional demands fall more on forward commands or on sensory processing [15], the need to locate and orientate the body in 3-D space for the purpose of posture control has naturally focused attention on the possible modulating effects of spatial cognitive tasks. A continuing line of enquiry in this regard asks whether interference in posture control occurs more by spatial memory tasks drawing on visual or visual-imagery processes, or by verbal (i.e., speech-based linguistic) tasks that are traditionally assumed to invoke a different processing stream ([77]; see [17; 134]). In early studies, negative patterns of dual-task interference were found for spatial memory but not verbal memory tasks [116; 151]. Recent work, however, has demonstrated interference between posture control and both verbal and spatial tasks ([63; 64; 107; 208; 248] and, marginally, [150]).

The discordant results between reports might be due in part to problems in controlling for task difficulty across secondary tasks, although improved reliability can be had from statistical analysis of task performances [107; 77; 267] or physiological markers of task load [77]. In some cases, experimental procedures may be an explanatory factor. For example, Brooks' spatial matrix task [39]—frequently employed to test for spatial cognitive interference in posture control [15; 116; 150; 151; 248]—could be performed (in principle) using covert verbalization of the sequence of directions for the spatial activity. Also, the verbalized instructions could act as a direct source of interference. A further complicating factor is that posture-cognition studies claiming similar investigative goals have differed according to the precise cognitive function being studied. Whereas some experimental designs have used tasks that centre on spatial attentional processes, such as speed of visual processing [62; 63], others have used tasks more obviously designed to tap memory functions [116; 150; 151; 208; 248]. While attention and memory are thought to be functionally linked [16; 201], the precise attentional demands and characteristics of these processes are not fully understood. This could potentially frustrate attempts to compare posture-cognition outcomes for the two types of tasks.

A further and more general issue is that experimental designs have differed in terms of whether the secondary task is more demanding of cognitive or perceptual resources in its interaction with the balancing task. Memory-based tasks designed to tap internal visuospatial processes tend to have little or no perceptual load (for instance, simply requiring the subject to visually fixate a point while mentally encoding or retrieving verbally presented information, see, e.g., [150; 151]). These tasks offer few opportunities for perceptual-based, postural-cognitive synergies. Perceptual-cognitive tasks, in contrast, may involve operations that can be synergized off the postural control task (e.g., line orientation judgments [35; 235]), or else provide perceptual information relevant to posture control. This information could be used to help anchor balance, and so attenuate any negative effect of the dual-task's cognitive component on postural stability (see, e.g., [108], for a visual-verbal task, and [70], for an auditory task). For these reasons, researchers interested in 'pure' cognitive load effects on postural control have looked to minimize the perceptual (as well as motor) content of secondary tasks [15; 217]

Such an approach might be limited in reach, however, with respect to its clinical interest or its relevance to everyday posture-cognition tasks. This is because postural control often has the dual-purpose of securing the body’s safety and balance while providing a stable physical substrate for perceptual-cognitive tasks. Beyond the basic requirement of keeping the centre of mass within the stability boundary, changes in sway amount or variability may have to do with postural operations that facilitate the acquisition of perceptual information for the suprapostural task [222; 245; 246]. In one study [245], for example, young adults fixated on either a cognitively-low (blank) target or on a cognitively-demanding target (requiring counting the frequency of letters in a block of text) while in upright stance. Target distance of the fixated items (near vs. far) was also manipulated. Both fixation on near targets as opposed to more distance targets, and fixation on the cognitively demanding target as compared to the cognitively-low target, brought about reduced sway variability. It was suggested that the need in each case to visually fixate the target placed restrictive constraints on the visual system, and which promoted reduced sway in support of the visual task [245].

As earlier discussed, an important but often underestimated consequence of the facilitatory-control view of posture-cognition dual-tasking is that increased sway as a function of cognitive-load cannot be automatically interpreted as indicating postural destabilization. Equally, a decrease in sway amplitude (or greater frequency of sway) in response to added cognitive task load cannot be reliably interpreted as a bracing action to protect posture [62-64; 268] (e.g., by increasing muscle stiffness

[5; 47; 48]). Nor can decreased sway be simply understood as reflecting increased attentional recruitment due to arousal or emotion [14], or as, say, a release of postural control from attentional focus [82; 157; 268].

As mentioned , this thesis employs control experiments that de-confound facilitatory and autonomous control explanations of postural sway. But the facilitatory control view has further importance in that it underscores the fact that posture has dual role in securing the body's safety and stability while providing a postural substrate well-suited to task-oriented perception-action [215]. In this respect, the ease with which a given task context can be embedded within the broad behavioural context enabled by posture control can be just as critical to the level of effort and skill the pairing requires, and the level of fluency it can be expected to achieve. In this sense, the act of setting up and maintaining a cognitive *task space* may have a cost to posture control, especially if the cognitive and postural task spaces are non-coincident and the relation between them is dynamically complex. It is to this issue of the co-registration of task-spaces for postural and cognitive tasks that the chapter now turns.

2.4 Frame co-registration cost hypothesis

Maintenance of upright stance minimally involves monitoring the motion of the body's COM and applying a pattern of forces across body segments to keep the body's line of gravity comfortably within the support base provided by the stance

[147]. Thus, the task-space with respect to which balance is maintained is naturally a *world-frame*, since the forces that need to be generated to keep the body upright result directly from the motion of body segments with respect to an inertial reference frame that is always anchored to the ground surface, and has one axis parallel to the direction of gravity (see Figure 2-1, page 39). On the cognitive side, humans are capable of configuring themselves, physically as well as cognitively, into special-purpose systems for efficiently performing many different functions. A notable feature of this versatility is that these tasks are of a bewildering variety of dimensions, both spatial and abstract, such that the cognitive task-spaces are highly flexible and apparently assembled on demand (see [254; 255], for illustrations from dynamic systems and motor learning). Most everyday cognitive tasks have prominent spatial aspects, but the most natural reference frame with respect to which a cognitive task is performed (call it the *task-frame*) may or may not be coincident to the world-frame.

For example, consider the case of standing upright as the postural task and searching for a visual pattern, say, a particular a word within a piece of text, as the cognitive task. Standing upright on a flat surface involves monitoring the motion of the body's centre of mass, and applying a pattern of forces across body segments to keep the body's line of gravity comfortably within the support base provided by the stance. The reference frame with respect to which tasks such as reading or visual search are performed is, on the other hand, a more complex issue. It is useful to note that the task of detecting the target word from a piece of text involves working with a set of visual features that appear in a particular spatial arrangement *with respect to each other*. It may be expected, then, that the most natural or most preferred reference frame for this task will be the one with respect to which the relative positions of visual features is specified in the most reliable and stable manner. If the display surface is ground-fixed (e.g., a wall or billboard), then the coordinates of the visual features with respect to the task-frame do not change relative to their coordinates with respect to the world-frame. In this sense, the postural and cognitive-task frames coincide. If the surface is, say, the side of a moving vehicle, or even a piece of paper held in the reader's hands, the dynamic relationship between this task-frame and the world-frame can become quite complex. In the latter, perhaps more general, case of postural-cognition dual-tasking, the visual search coordinates are placed in a task-linked reference frame that can move with respect to the world-frame. In this sense, reference frames for the two tasks do not always coincide.

There can be two types of solutions to this problem of non-coincident task frames. One requires ongoing effort, and is therefore expected to generate performance costs. The other is a matter of choice without ongoing effort, and should not impact dual-task performance. To take the latter case first, one possibility is that performing a cognitive task such as reading or visual search in its natural reference frame does not impede simultaneous control of body posture with respect to the world-frame. If this is the case, then frame discrepancy is a non-issue. A second possibility is that discrepancy between the two tasks' natural frames is an issue, but both tasks can simply adopt one or the other task's natural frame as a common frame for dual-task performance. In either case, there is no expectation of dual-task performance costs associated specifically with non-coincidence of task frames. The second type of solution involves performing each task in its most natural reference frame, but requires some (effortful) means of always keeping the task- and world-frames in register. Such a co-registration process could mean maintaining the transform that takes one frame to the other to allow working in a common reference frame, or it could mean keeping the world- and task-frames separate, but updating the state with respect to each frame at a rate that falls within the tolerance limits of both tasks (i.e., the motion of one frame relative to the other would have to be monitored to avoid disorientation). Either way, if the solution involves ongoing effort, the process is referred to here as frame co-registration, and any associated costs to postural or cognitive task performance as co-registration costs. *It is hypothesized that when performing a cognitive task, such as reading or visual search, alongside a postural task, such as maintaining upright stance, non-coincidence of the two tasks' natural reference frames is not resolved automatically, but by a co-registration process involving costs to postural performance*. The following sections (2.4.1) refine the notion of a natural reference frame for the visual search and mental rotation tasks employed to test the frame co-registration cost hypothesis, and (2.4.2) present the experimental design in further outline.

2.4.1 Natural reference frame for the cognitive task

The target of a visual conjunction search [259] is defined by the simultaneous presence of certain features at a particular location in the visual field. Whether selection by location is given a special status [259; 284] or not [43; 113], location information is logically prior to, and has important role in, any object-based visual search process (see [216], for a consideration). To unambiguously localize an object it is necessary to select a particular reference frame and specify locations with respect to that reference frame [122]. A given task situation typically offers a choice between multiple egocentric (e.g., eye-centred, head-centred, shoulder-centred) and exocentric (e.g., world-centred, object-centred, display-centred) reference frames (see, e.g., [27; 45; 46; 61; 80; 114]). Exocentric frames, which are defined in terms of relations between external objects (or portions or elements of objects), provide the most stable and reliable means of storing item locations if the relative position of items is of considerable interest [185]. This is commonly asserted as the case for object recognition tasks [270], but evidence of oculomotor memory in visual search [88; 121; 152; 200] suggests that the location of display items with respect to each other is also important in a task such as conjunction search.

If the choice of reference frames is essentially unlimited, in what sense can the cognitive component of a postural-cognitive dual-task have a natural or preferred reference frame that is worth retaining, even when it is non-coincident with the postural component's world-frame? Kunde and Hoffman [122] have recently shown, using a paradigm requiring participants to localize search targets either relative to the character configuration in which they were embedded (egocentric coordinates) or relative to the presentation screen on which the configurations were displayed (exocentric coordinates), that the propensity to localize a search target with respect to a given reference frame increases as the uncertainty of location with respect to that frame decreases. Applied to the present context, Kunde and Hoffman's [122] least-uncertainty principle would advise that a natural reference frame for the visual search task is a screen-based, exocentric reference frame, by the following logic. While performing visual search, the searcher's eyes move relative to the head, and the head moves relative to the world. The search display itself can be in motion relative to the world or the searcher's eyes or head, but as long as groups of items on the search display do not move relative to each other, the least uncertain coding of their locations is always with respect to an exocentric reference frame anchored on the search display itself. Therefore, in the design of the visual search experiments, the coincidence and non-coincidence of postural and cognitive task-frames were determined from the relative motion of the postural task's world-frame and the visual search task's display-anchored exocentric frame.

Regarding a natural reference frame for mental rotation, this extensively researched paradigm requires participants to decide whether one of a pair of 3-D objects, rotated in the picture plane or in depth, is a copy or mirror of the identity (i.e., reference) object. Typically, response latency is found to increase linearly with the angle of displacement between identity and parity/non-parity figures [55-57; 232;

288; 297; 298]. Since an approximate linear relationship between response time and angle of displacement in the matching process is also found for the rotation of actual objects, the linear relationship in the internal process of object matching has been interpreted as evidence that participants mentally rotate one object into congruence with the other [55; 56; 232]. In this sense, these studies would advise that the natural reference frame for the mental rotation task is a display-anchored exocentric task-frame, in which observers mentally rotate (or otherwise compute) the axes of the one object into congruence with that of the second object, rather than utilizing the perspective of the viewer.[6]

2.4.2 Testing the frame co-registration cost hypothesis

Immersive visualization was used to allow full control over the relationship between the postural world-frame and the cognitive task-frame. For the visual search experiments, in the *coincident frames* condition, the conjunction search task was presented on a head-mounted display, and a head-mounted motion tracker (Polhemus Fastrak) used to update the participant's swaying viewpoint in real-time (Figure 2-1). Phenomenologically, the task-frame in this condition remained static

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[6] The interpretation of a linear relationship between response time and displacement angle as reflecting physical rotations has been criticised on grounds that many mental imagery tasks are found to be cognitively penetrable [205], and that mental rotation is a visually complex task ([25; 98]; but see [233]). Regardless of the actual matching process underlying the mental process however, mental rotation for static displays is thought to be based on object orientation, because the viewpoint of the observer always remains the same [266].

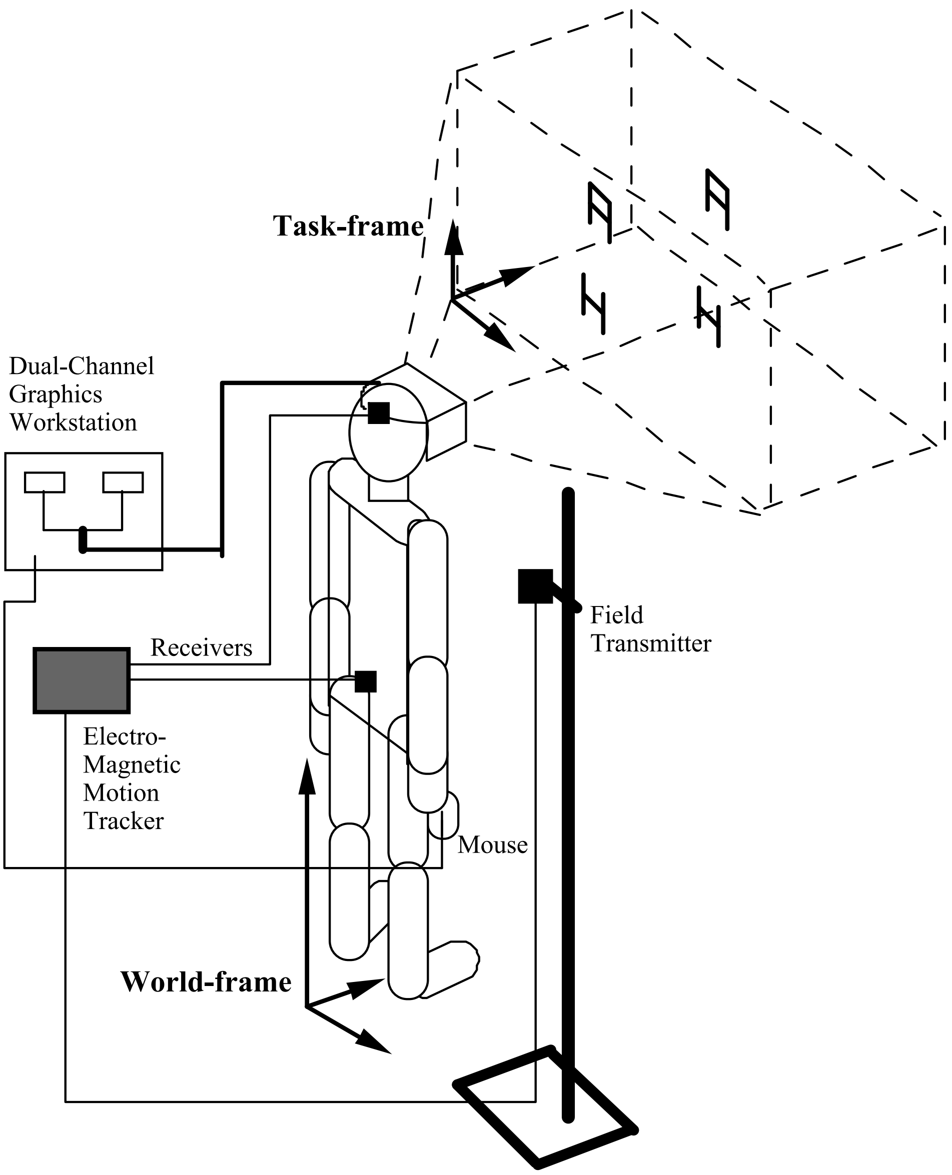

Figure 2-1. Schematic diagram of the experimental setup. As shown, the task-space for standing upright was the world-frame, with one axis parallel to gravity. The task-frame for the search task was attached to the bounding volume of the stimulus set. The stimuli were viewed through a stereoscopic head-mounted display. Postural sway was recorded from the participant's head and hip segments using an electro-magnetic motion-tracker. In the basic manipulation (Experiments 2 and 3), in the *coincident frames* condition, head sway information was used to change the location of the viewpoint in the world-frame (i.e., from the participant's perspective, the search items remained static in the world-frame). In the *non-coincident frames* condition, the search items moved with the swaying head. Participants responded using a two-button mouse held in the dominant hand.

with respect to the world-frame. Thus, the natural frame for the search task coincided with the postural world-frame. Since the aim of Experiment 1 (Chapter 4) was to simply establish if resource-sharing conditions could be altered according to (postural or cognitive) task requirements (rather than as a test of the frame co-registration cost hypothesis), in this experiment the frames for the postural and search tasks were designed to always coincide.

In Experiments 2 and 3 (Chapter 5), a *non-coincident frames* condition was added. This condition differed only in that the stimuli remained static not with respect to the world-frame, but with respect to the participant's viewpoint. The display-anchored, exocentric task-frame therefore remained anchored to a reference frame attached to the participant's head, which swayed spontaneously (with respect to the world-frame) as the participant maintained upright stance. Since, as discussed in Chapter 2, the spontaneous body sway associated with standing upright has high dimensional dynamics, the latter condition of having the motion of the search task's display mirror the motion of the participant's swaying head gave a task-frame that was dynamically uncoupled from the world-frame: as the participant stood and performed the visual search, he or she could not solve the frame discrepancy by mapping the task-frame on to the world-frame by applying any low-dimensional motion equation. However, as there were multiple sources of information (vestibular, proprioceptive, etc.) about sway available to the participant's nervous system on a continuous basis, the cognitive task-frame was not arbitrarily related to, or informationally uncoupled from, the postural world-frame. *The main* *experimental prediction of the frame co-registration cost hypothesis was that the non-coincident frames condition would generate a greater performance cost to posture control than performing visual search in the coincident frames condition.* As introduced, to investigate any interactions between frame coincidence and task-load, the postural component's load was manipulated by requiring that participants stand in either open or closed stance. Cognitive task-load was manipulated by varying the number of items (set size) in the display for the conjunction search task.

In Experiment 2, participants were instructed to focus on the visual search task, but in Experiment 3, they were instructed to also minimize sway. This manipulation was expected to alter the balance of effort allocated to the postural and cognitive task components, and allow closer examination of any frame co-registration costs.

As is discussed in detail in Chapter 6, one consequence of the frame manipulation was that participants had access to the optic flow generated by their own sway in the coincident frames condition only, and which might advantage postural control in this condition. To eliminate this potential confound, the basic frame manipulation was refined in Experiments 4 to 5 by splitting the search stimuli equally across the world and task-frames, with the target item appearing in the world-frame in the coincident frames condition and in the head-anchored task-frame in the non-coincident frames condition. In Experiment 4, participants were instructed to focus on the visual search task, but in Experiment 5, they were instructed to also minimize sway.

Though the vast majority of research on visual search has been carried out on planar search displays, real-life visual search is manifestly more common in three dimensions. In contrast to Experiment 1, in which the visual search display was a planar surface, Experiments 2 to 5 used a fully 3-D version of the visual search task in which each item in the display appeared at random locations within a fixed display volume. To assess whether introducing depth in the search displays affects the pattern of dual-task performance, Experiment 6 compared participants' performance in coincident and non-coincident frame conditions across 2-D and 3-D search display layouts.

The visual search experiments examined the co-registration hypothesis in context of items located in the extrapersonal world (i.e., external space). Given the suspected involvement of feedforward representations in the sensorimotor calibration process , and the body-referential processes underlying cognitive processes [68; 89; 91; 92; 112; 277], it is possible that postural control costs of non-coincident frames may be involved for cognitive operations that occur on internally generated and maintained representational states, as for example, the mental manipulation of objects. In Experiment 7, the frame co-registration cost hypothesis was tested using a mental rotation task in which participants performed parity/non-parity judgments for an identity object, in which the object pair were placed in either coincident or non-coincident reference frames. Again, to investigate any interactions between frame coincidence and task-load, the postural component's load was manipulated by requiring that participants stand in either open or closed stance. Cognitive task-load was manipulated by varying the size of the displacement angle between identity and parity/non-parity objects. A frame co-registration cost hypothesis would predict that the non-coincident frames condition should generate a greater performance cost to posture control than performing mental rotation in the coincident frames condition, over and above any costs of postural or cognitive task-load.

Table 2-1 Literature review of previously conducted research on concurrent tasks during upright stance

Notes.

(1) Key to postural measures

Balance control measures: acronyms, descriptions and measures	
(Parameters computed from ML, AP, and 2-D COP displacements)	
MD	Mean distance from centre of COP trajectory, mm
RMS	Root mean square of COP time series, mm
SD	Standard deviation distance from the mean COP, mm
SP	Sway path, total COP trajectory length, mm
RANGE	Range of COP displacement, mm
MV	Mean velocity of the COP (SP/T^*), mm/s^{-}
MPF	Mean power frequency—revolutions per second of COP to travel total trajectory equal to SP ($MF = SP/(2\pi - MD – T^*)$), Hz
SDmw	Moving window standard deviation—mean moving SD of the COP or COM time series, mm/s
RMSmw	Root mean square of the mean moving SD of the COP or COM time series, mm/s
(Parameters computed from 2-D COP displacements only)	
CEA	Confidence ellipse area, 95% confidence ellipse
SA	Sway area, computed as COP displacement per unit of time

T, duration of a trial, s (Following [223])

(2) Reported changes in balance and cognitive task performances are with respect to postural (seated or quiet standing) and cognitive (no explicit cognitive task) baseline conditions, unless otherwise indicated. Reported effects of postural and cognitive difficulty levels were nil (no difference between levels), unless otherwise indicated. Differences between test populations and between dual-task (postural, cognitive, vision) conditions were nil, unless otherwise indicated. ML = medial-lateral sway and AP = anterior-posterior sway directions.

Dual-task	Population	Sway Instr.	Effect of cognitive task	Effect of postural task	Study
Unperturbed wide-base standing **Spatial attention (visual)** • Manikin task (2 levels) .	Young (n = 15) and older adults (n = 15)	Instruction to "stand quietly"	Young adults: **Posture sway decreased** • RMS-ML, RMS-AP decreased • MPF-ML, MPF-AP increased Older adults: **Posture sway increased** • RMS-ML, MPF-ML increased* *Increased frequency with no change in amplitude interpreted by the authors as indicating decreased posture control	**Cognitive task performance unchanged**	Dault & Frank (2004)
Unperturbed wide- and narrow-base standing **Spatial attention (visual)** • Conjunction visual search (2 levels)	Young adults (n = 17)	None/Not stated	**Posture sway increased** • SDmw-ML, RMSmw-ML, RMSmw-AP increased in narrow-base standing (*high cognitive load only*)* *Relative to dual-tasking in wide-base standing	**Cognitive task performance increased** • RT decreased in narrow-base standing	Mitra (2003)
Unperturbed wide- and narrow-base (tandem) standing **Spatial attention (visual)** • Manikin task (2 levels) **Non-spatial attention** • Word categorization task **General attention** • Random number generation	Young adults (n = 22)	Instruction to "stand quietly"	**Posture sway decreased** • RMS-ML decreased in narrow-base standing (*spatial and general attention tasks*) • RMS-AP decreased in wide- and narrow-base standing (*all cognitive tasks*) • MPF-ML increased in narrow-base standing (*spatial and non-spatial tasks*) • MPF-AP increased in wide-base standing *(all cognitive tasks*)	**Cognitive task performance unchanged**	Dault, Frank et al. (2001)

Unperturbed and perturbed wide-base standing **Spatial attention (visual)** • Line orientation task (verbally reported) **Non-spatial attention** • Sentence completion task (verbally reported)	Young adults (*n* = 20), and older adult fallers (*n* = 20) and non-fallers (*n* = 20)	Instruction to “hold still as possible”	Young adults: **Posture sway increased** • SP increased (*spatial task*) Non-fallers: **Posture sway increased** • SP increased (*spatial task*) • Sway increase greater than in young adults Fallers: **Posture sway increased** • SP increased (*all cognitive tasks*) • Sway increase greater than in young adults and non-fallers	**Cognitive task performance unchanged**	Shumway-Cook et al. (1997)
Unperturbed and perturbed wide-base standing **Spatial attention (auditory)** • Low- (speeded discrimination) and high-load (forced choice) auditory-spatial RT tasks **Non-spatial attention** • Low- (speeded discrimination) and high-load (forced choice) verbal RT tasks	Vestibular patients (*n* = 48) and controls (*n* = 24)	None/Not stated	**Posture sway unchanged**	All adults: **Cognitive task performance decreased** • RT decreased in perturbed standing (*all cognitive tasks, low cognitive load only*) • Errors increased in perturbed standing (*all cognitive tasks, high cognitive load only*) • Greater errors on spatial task	Yardley et al. (2001)
Unperturbed and perturbed wide- and narrow-base standing **Non-spatial attention** • Auditory probe RT stimulus	Young (*n* = 8) and older adults (*n* = 9)	Instruction to “maintain a stable upright posture”	**Posture sway unchanged**	**Cognitive task performance decreased** • RT decreased in perturbed wide- and narrow-base standing • RT increase greater in older adults	Teasdale et al. (1993)

Unperturbed and perturbed wide- and narrow-base (tandem) standing **Visuo-verbal attention** • Stroop task (3 levels)	Young adults (*n* = 24)	Instruction to "stand quietly" Minimum distribution of anterior body weight required for a seesaw standing condition	**Posture sway decreased** • RMS-AP decreased, MPF-ML, MPF-AP increased in perturbed wide-base standing (*all cognitive tasks*) • MV-ML decreased, MPF-ML and MPF-AP increased in perturbed narrow-base standing (*spatial and general attention tasks*)* *Increased velocity together with increased frequency interpreted by the authors as indicating decreased postural control	**Cognitive task performance unchanged**	Dault, Geurts et al. (2001)
Unperturbed wide- and narrow-base standing **Visuo-verbal attention** • Stroop task	Young (*n* = 20) and older adults (*n* = 20)	Instruction to "stand still…as possible"	Young adults: **Posture sway increased** • SD-ML, SP, MV, CEA increased in wide-base standing • SP, MV increased in narrow-base standing Older adults: **Posture sway increased** • SD-ML, SD-AP, SP, MV, CEA increased in wide-base standing • Sway increase greater than in young adults Older adults: **Posture sway decreased** • SD-ML, CEA decreased in narrow-base standing	Not examined	Melzer et al. (2001)

Unperturbed wide-base standing **Visuo-verbal attention** • Stroop task (3 levels) **WM** • Backwards counting (verbally-reported)	Older adults ($n = 40$)	Instruction to “remain as stable as possible”	**Posture sway increased** • SA increased (*WM task*)	Not examined	Jamet et al. (2004)
Unperturbed wide-base standing **Visuo-verbal attention** • Stroop task (3 levels) **WM** • Backwards counting (verbally-reported) **Spatial attention** • RT probe location task	Young ($n = 26$), middle-aged ($n = 26$) and older adults ($n = 28$)	Instruction to “remain as stable as possible”	Young adults: **Posture sway marginally decreased** • SA, AP amplitude decreased (*Stroop task*) Middle-age and older adults: **Posture sway increased** • SA and AP amplitude increased (*WM task*) Young and middle-aged adults: **Posture sway decreased** • SA, ML and AP amplitude decreased (*spatial attention task*)	Not examined	Jamet et al. (2006)
Unperturbed and perturbed narrow-base (tandem) standing **Visuospatial WM** • RT probe location-tracking task (2 levels) **Visual object WM** • RT probe object-tracking task (Attneave shapes, 2 levels)	Young adults ($n = 9$)	Instruction to “remain steady and stable”	**Posture sway unchanged**	**Cognitive task performance decreased** • RT decreased in unperturbed and perturbed standing (*spatial task, high cognitive load only*)	Vander-Velde et al. (2005)

Unperturbed wide-base standing **Visuospatial WM** • Visuospatial N-back task (2 levels) **Non-spatial WM** • Digit N-back task (2 levels) **General attention** • RT forced-choice digit task (2 levels)	Young (*n* = 20) and older adults (*n* = 20)	Instruction to “stand as still as possible”	Young adults: **Posture sway increased** • CEA increased (*all cognitive tasks, high cognitive load only*) Older adults: **Posture sway increased** • CEA increased (*all cognitive tasks*)	**Cognitive task performance unchanged**	Huxhold et al. (2006)
Unperturbed wide-base standing **Spatial WM** • Modified Brooks’ spatial task (encoding phase only) • Backward digit recall **Non-spatial WM** • Modified Brooks’ verbal task (encoding phase only) • Backwards counting (verbally-reported) **General attention** • Random digit generation (verbally-reported)	Middle-aged (*n* = 19) and older adults (*n* = 19)	Instruction to “remain steady as possible” Posture control explicitly stated as being the primary task	Middle-aged adults: **Posture sway decreased** • SD-AP decreased (*spatial WM and digit recall tasks*) Older adults: **Posture sway increased** • SD-AP sway increased (*spatial WM and digit recall tasks*)	All adults: **Cognitive task performance increased** • Less time to completion (*silent counting task*) All adults: **Cognitive task performance decreased** • Less random production (*random digit generation task*)	Maylor & Wing (1996)

Unperturbed wide-base standing **Spatial WM** • Modified Brooks' spatial task (encoding and maintenance phases, 2 levels) **Non-spatial WM** • Modified Brooks' spatial task (encoding and maintenance phases, 2 levels)	Young and older adults (n = 70) Eleven or twelve adults in each of the six decades from 20s through to 70s	Instruction to "stand still as possible" Equal emphasis given to postural and cognitive tasks	All adults (encoding phase): **Posture sway decreased** • SD-ML, SD-AP, MV decreased (*spatial task and, marginally, non-spatial task*) All adults (maintenance stage): **Posture sway increased** • In young adults, SD-ML, SD-AP and MV decreased, MV increased (*spatial and non-spatial tasks*) • In older adults, SD-ML, MV increased (*spatial and non-spatial tasks*)	**Cognitive task performance unchanged**	Maylor et al. (2001)
Unperturbed narrow-base (tandem) standing **Spatial WM** • Modified Brooks' spatial task **Non-spatial WM** • Modified Brooks' verbal task	Young adults (n = 24)	None/Not stated	**Posture sway unchanged*** * Significant reduction in sway from the baseline condition explained as due to a significant order-condition effect	**Cognitive task performance decreased** • Accuracy decreased (*spatial WM task*)	Kerr et al. (1985)
Unperturbed and perturbed wide-base standing **Spatial WM** • Modified Brooks' spatial task (encoding phase only) **Non-spatial WM** • Modified Brooks' verbal task (encoding phase only)	Young (n = 18) and older adults (n = 15)	Instruction to "hold still as possible"	Older adults: **Posture sway decreased** • SD-ML, SD-AP decreased in perturbed standing, eyes closed	**Cognitive task performance unchanged**	Swan et al. (2004)

Perturbed wide-base standing **Spatial WM** • Modified Brooks' spatial task	Vestibular patients (*n* = 24) and matched controls (*n* = 24)	None/Not stated	In patients and controls: **Posture sway increased*** • AP peak amplitude increased * In a subset of patients failing a posturography test, posture sway decreased	**Cognitive task performance decreased** • Accuracy decreased *Eyes open and eyes closed conditions in controls. Eyes closed condition only in patients	Andersson et al. (1998)
Unperturbed wide-base standing **Spatial WM (auditory)** • Rotary-surround auditory recall **Non-attentive** • White noise	Older adults (*n* = 32)	Instruction to "remain as stable as possible"	**Posture sway decreased** • ML amplitude, SA decreased (*spatial WM task*)	Not examined	Deviterne et al. (2005)
Unperturbed wide-base standing **Visuo-WM** • Colour identification task (2 levels)	Young adults (*n* = 6)	Instruction to "remain immobile as possible"	**Posture sway decreased** • RANGE-ML, RANGE-AP decreased	Not examined	Vuillerme et al. (2000)
Unperturbed wide-base standing **Non-spatial WM** • Backwards counting (2 levels)**—**presentation mode not specified	Young adults (*n* = 20), and older adult fallers with (*n* = 20) or without (*n* = 20) cognitive impairments	Instruction to "hold position" Explicit instruction to give equal emphasis to postural and cognitive tasks	Cognitive-impaired: **Posture sway increased** • SD-ML, SA increased	**Cognitive task performance unchanged**	Hauer et al. (2003)

Unperturbed wide-base standing **Non-spatial WM** • Comprehension task • Backwards counting (silent) **Non-attentive** • White noise	Young adults (n = 39)	Instruction to “stand still as possible”	**Posture sway increased** • SD-AP sway increased, as did activation of ankle and hip extensors correlated with the forward leaning (*backwards counting task*)	Not examined	Maki & McIlroy (1996)
Unperturbed narrow-base (tandem) standing **Non-spatial WM** • Arithmetic addition task (3 levels) presented in visual and auditory modalities, and performed with or without eye movement	Young adults (n = 30)	None/Not stated	**Posture sway decreased** • SD-ML sway decreased • Greater ML variability in eye movement than no-eye movement condition	**Cognitive task performance unchanged**	Hunter & Hoffman (2001)
Unperturbed wide-base standing **Non-spatial WM** • Backwards counting (verbally-reported) **Motor task** • Sequential finger movement task	Parkinson’s patients (n = 24) and controls (n = 20)	Instruction to “stand still as possible”	Patients: **Posture sway increased** • CEA increased • Sub-analysis of pd fallers (n = 8) and SD non-fallers (n = 16) showed that sway increase was greater in PD fallers	Not examined	Marchese et al. (2003)
Unperturbed wide-base standing with or without focal (central) vision **Non-spatial WM** • Arithmetic task **Motor task** • Finger-thumb pinch task	Young (n = 18) and older adults (n = 18)	None/Not stated	All adults: **Posture sway decreased** • SD-ML sway decreased (*non-spatial WM task*) Note. Postural sway increased on motor task	**Cognitive task performance unchanged**	Weeks et al. (2003)

Unperturbed and perturbed wide-base standing **Non-spatial WM** • Auditory speed discrimination task (verbally-reported)	Young (*n* = 14) and older adults (*n* = 18)	Explicitly states posture control as being the primary task	**Posture sway increased** • SD-ML, SD-AP, RANGE-ML, RANGE-AP, MV, SP, CEA, SA increased	**Cognitive task performance unchanged**	Marsh et al. (2000)
Unperturbed and perturbed wide-base standing **Non-spatial WM** • Digit rehearsal task (2 levels) in visual (Exp1) and auditory (Exp 2) modalities	Young adults *n* = 23 (Exp 1) *n* = 20 (Exp 2)	Participants told not to focus exclusively on either task, but to perform the WM task as accurately as possible	**Posture sway decreased** • MWSD-ML sway decreased under high cognitive load (*both experiments*)	Not examined	Riley et al. (2005)
Unperturbed wide- and narrow-base (tandem) standing; unperturbed and perturbed single-limb (arm raise) standing **Non-spatial WM** • Backwards recital	Older-to-middle-aged Parkinson's fallers (*n* = 15) and non-fallers (*n* = 15), and controls (*n* = 15)	None/Not stated	Not examined	All patients and controls: **Cognitive task performance decreased** • Completion rate decreased in arm-raise condition PD fallers: **Cognitive task performance decreased** • Completion rate decreased in narrow-base standing	Morris et al. (2000)

Unperturbed and perturbed wide-base standing **Non-spatial WM** • Forced choice auditory discrimination task (verbally-reported)	Young adults (*n* = 18), and older adult fallers (*n* = 18) and non-fallers (*n* = 18)	Instruction to "stand still as possible"	Older non-fallers: **Posture sway increased** • SP increased in eyes closed, sway-referenced optokinetic stimulation condition Older adult fallers: **Posture sway increased** • SP increased in all sensory conditions* *On those dual-tasks that could be completed—fallers were unable to stand under the most challenging sensory contexts, and so were excluded from performing in these contexts under dual-task conditions	Older adult fallers and non-fallers: **Cognitive task performance decreased** • RT decreased in perturbed standing	Shumway-Cook & Woollacott (2000)
Perturbed wide-base standing **Non-spatial WM** • Silent backwards counting Exp 2 as for Exp.1 but with inter-trial postural focus condition	Young adults *n* = 30 (Exp 1) *n* = 20 (Exp 2)	Exp.2 only: Explicit instruction to monitor balance control *between* cognitive task trials	In Exp.1, **posture sway decreased** • Torque variance increased In Exp. 2, **posture sway decreased, but effect attenuated** • Torque variance increased	In Exp.1, **cognitive task performance decreased** • Completion rate decreased In Exp 2, **cognitive task performance unchanged**	Andersson et al. (2002)
Perturbed wide-base standing **Non-spatial WM** • RT forced choice auditory task (verbally-reported)	Young adults (*n* = 15), and balance-impaired older adults (*n* = 15) and controls (*n* = 13)	Participants "instructed to keep their balance"	Young adult and controls: **Posture sway decreased** • RANGE-AP decreased Balance-impaired: **Postural sway increased** • Stabilization time, MV increased	Patients and controls: **Cognitive task performance decreased** • RT decreased • RT increase greater in patients than controls	Brauer et al. (2001)

Perturbed wide-base standing **Non-spatial WM** • RT forced choice auditory task (verbally-reported)	Young (*n* = 15) and older adults (*n* = 10)	Participants instructed “avoid using a step to recover their balance”	**Posture sway increased** • Change in kinematics observed for strategy**—**step responses were closer to the base of support	All adults: **Cognitive task performance decreased** • RT decreased • RT increase greater in older adults than young adults	Brown et al. (1999)
Perturbed wide-base standing **Non-spatial WM** • Digit reversal, classification • Backwards counting (presentation mode unspecified)	Young adults (*n* = 20)	None/Not stated	**Posture sway increased** • RANGE-ML, RANGE-AP increased (*classification task*) • SP, SD-AP, RANGE-ML, RANGE-AP increased (*backwards counting task*)	Not examined	Pellecchia (2003)
Perturbed wide-base standing **Non-spatial WM** • Backwards counting (presentation mode unspecified)	Young to middle-age adults (*n* = 18)	None/Not stated	**Posture sway increased** • SP increased	Not examined	Pellecchia (2005)
Perturbed wide-base standing **Non-spatial WM** • Digit rehearsal task (2 levels)	Young adults (*n* = 23)	None/Not stated	**Posture sway decreased** • SD-AP sway decreased (*high cognitive load only*)	Not examined	Riley et al. (2003)

Unperturbed and perturbed wide-base standing **General attention without motor task** • Silent counting **General attention with motor task** • Articulation task (2 levels) **Motor task** • Jaw open and close	Young adults (*n* = 20)	None/Not stated	**Posture sway decreased** in all dual-task conditions, but by a lesser amount with tasks involving verbalized responses • RMS-ML, RMS-AP decreased (*all tasks except silent counting*) • MPF-AP increased (*all tasks except silent counting and motor tasks*) • SP decreased (*articulation task*)	**Cognitive task performance unchanged**	Dault et al. (2003)
Perturbed wide-base standing **Attentional focus** • Control of finger-to-sheet contact, either to minimize the movement of a draped sheet (external focus), or to minimize the movement of finger (internal focus)	Middle-aged adults (*n* = 19)	Participants required to focus on the postural task (internal focus) or on the consequences of balance for the cognitive task (external focus)	**Posture sway increased** • MWSD-ML, MWSD-AP sway increased • MPF increased in external focus condition only	Not examined	McNevin & Wulf (2002)
Unperturbed and perturbed wide-base standing **Inhibitory task** • 'Stop-Go' visual-auditory inhibitory RT **t**ask **General attention** • Simple and forced choice RT auditory tasks	Young (*n* = 18) and older adults (*n* = 18)	None/Not stated	Older adults: **Posture sway increased** • RMS-AP sway increased in body and visual sway-referenced condition	Young and older adults: **Cognitive task performance decreased** • RT decreased in perturbed standing	Redfern et al. (2001)

Unperturbed and perturbed wide-base standing **Inhibitory task** • 'Stop-Go' visual-auditory inhibitory RT **t**ask **General attention** • Simple and forced choice RT auditory tasks	Vestibular patients (*n* =15) and matched controls (*n* =15)	Instruction to "stand as still as possible" Equal emphasis given to postural and cognitive tasks	**Posture sway increased** • RMS-AP increased, MV decreased	Patients and controls: **Cognitive task performance decreased** • RT decreased in perturbed standing • RT increase greater in patients than controls	Redfern et al. (2004)

Chapter 3

Methodology

3.1 Methodology

This chapter describes the methodology used to generate, record and analyse the data for the investigation of the frame co-registration cost hypothesis. The first part describes methods to the visual search experiments, and the second part describes methods to the mental rotation experiment. Participant details, together with review of inter-experimental modifications, are prefaced immediately to each experiment in the respective chapter.

3.2.1 Apparatus and data collection

Basic apparatus design and data collection followed Mitra [162]. The visual stimuli were generated by a Silicon Graphics Onyx 3200 workstation (with InfiniteReality3 graphics), and presented through a Virtual Research V8 head-mounted display

(HMD) unit. The field of view in each eye (i.e., the angular subtense of the displayed image as measured from the pupil of one eye) was 60^0 diagonal (see Figure 3-1). Stimulus presentation was stereoscopic, with both channels rendered in-phase at each frame. Inter-pupillary distance was assumed fixed at 6.5 cm. Asymmetric viewing frustums were used for both eyes, with the point of convergence set at the participant's eye level, exactly in between the two eyes, and at a distance of 48 cm in front of the participant at the instant of calibration. The centre of the stimulus display (where the crosshair was located) coincided with this point of convergence. The total weight of the HMD unit was 1.0 kg, balanced about the centre of the head.

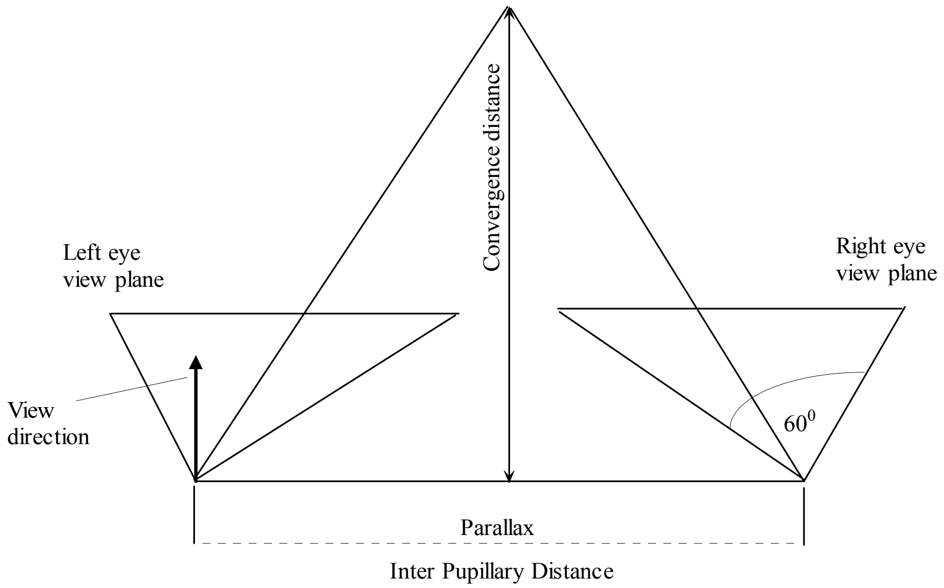

Figure 3-1 The HMD's field of view (following [79]).

The three position coordinates of the head were recorded and stored at the beginning of each screen refresh using a Polhemus Fastrak magnetic motion tracker attached to the HMD (see Figure 2-1, page 39). The recorded change in head position since the previous screen refresh was used to update the viewpoint location. For the *coincident condition*, the stimulus display appeared to maintain its position and orientation in the world-frame, with the observers' own head motion appearing to generate the expected changes in viewpoint. This ensured that, within the accuracy limits of the motion tracker (itself approximately 0.0012 cm RMS when static, with a latency of 0.004 s), all the optical consequences of postural sway were made available to the participants at locked frame rate of 60 Hz (i.e., 0.017 s effective update latency). The anterior-posterior (AP) component of sway gave rise to radial flow, the medial-lateral (ML) component of sway produced lamellar flow. In Experiments 2-6 only, motion parallax (i.e., changes in the optical separation between two or more search items as a result of sway) was generated due to presentation of the stimulus display in depth. Stereoscopic presentation also ensured that vergence control for binocular fixation on the search items provided information about head motion. Phenomenologically, this arrangement generated a strong impression that the stimulus display remained at the same point in space, and held its position and orientation in the task-space even as the participant's viewpoint changed continually due to postural sway.

In Experiments 2-6, the apparatus was used to generate a second, *non-coincident condition*, in which the stimulus display appeared and maintained position orientation with respect to the observer's head. Another way of describing the manipulation is through the dynamic relationship between the world-frame and the task-frame. In the non-coincident frames condition, the task-frame had the same motion with respect to the world-frame as the participant's swaying head. This arrangement meant that participants had no access to the optical consequences of their sway (on which, see Experiments 4-5, Chapter 6). Nonetheless, the difference between coincident and non-coincident trial blocks for the visual search tasks was phenomenologically subtle. When interviewed at debriefing, only one participant volunteered having noticed a difference between the two frame conditions (reporting, for the stimuli used in Experiments 2-3, that the world-frame stimuli appeared "more three-dimensional"). While a number of participants claimed to recognize the manipulation when they were told about it afterwards, the majority did not. The subtlety of this manipulation can be appreciated by noting that the magnitude of spontaneous head sway during unperturbed standing by healthy young adults is quite small (as is apparent from the means of the sway measures presented in the results to the experiments).

In addition to the head-mounted motion tracker used to generate the frame manipulation, in Experiments 2-6, participants wore a second receiver (attached to a Velcro belt) on their lower backs, approximately on the first lumbar vertebra. This tracker recorded the motion of the hip from the point on the body surface that is closest to the centre of mass during upright stance [42]. Hip motion was recorded for data analysis only, and not used in rendering the visual display. Responses to stimuli were collected via presses of the left and right buttons of a three-button mouse held in the participant's dominant hand. Responses were recorded at a resolution of 1 ms by a forked process running independently of, but in synchrony with, the 60 Hz graphics loop.

3.2.2 Stimuli

The visual search displays contained blue (RGB: 0.239, 0.451, 0.674) and green (RGB: 0.318, 0.62, 0.274) rectangular 'A' and 'H' letter shapes (see Figure 2-1, page 39). The coloured letters were of equal luminance, displayed against a black background. Each letter was 2.4 cm in height and 1.44 cm in width, and was composed of one vertical and one horizontal cylinder of the above lengths, respectively, and a diameter of 0.48 cm. The cylinders were approximated with a 6-polygon tessellation, and were gouraud-shaded. The entire stimulus set was lit by a single white light source from the above-left of the viewpoint. In Experiment 1, all search items were placed on the same depth plane. In Experiments 2-5, the search stimuli were staggered randomly in depth (± 10 cm around an average distance of 48 cm from the eyes). In Experiment 6, the visual search display was presented either as a planar surface at the convergence distance as in Experiment 1, or with the items randomly staggered in depth exactly as in Experiments 2 to 5.

Before each stimulus trial, a white fixation crosshair (composed of a cylinder of length 1.2 cm and diameter 0.24 cm) was presented in the world-frame for 1 s at the centre of an invisible 8 x 8 cell display grid (at the same depth as the point of convergence). Each display cell measured 5.76 cm in length and width. For each trial, the letter shapes were randomly assigned to display cells, and their vertical and horizontal positions within cells were further randomized within a 1.44 cm range. The proportion of the participant's field of view over which search items could range in any given trial remained constant across all conditions.

3.2.3 Experimental design and procedures

The search displays consisted of 4 and 16 (randomly-placed) items in the low and high search-load conditions, respectively. On target-absent trials, half the display items were green H's, and half the display items were blue A's. On target-present trials, the search target item, a blue H, replaced one of the blue A's. Each search block consisted of 20 target-absent and 20 target-present trials, randomly presented. Participants were instructed to press the left button of the hand-held mouse if the display in a given search trial contained a blue H, and the right button of the mouse if it did not.

The search task was performed while standing upright at a location marked with a cross on the laboratory floor. No footwear was worn, and arms were held relaxed by the sides of the body. For Experiments 1-5, postural difficulty was manipulated by using open and closed stances. In the open stance condition, participants took up stance either side of the marked cross, and stood with their heels about 10 cm apart, feet at about 45° to each other, In the closed stance condition, participants stood over the marked cross, with feet flush against each other. Other than these requirements, no formal methods were employed to control participants' stance. Experiment 6 was conducted in open stance only.

Prior to data collection, the experimenter assisted the participant with fitting of the Velcro belt (with the hip-motion tracking sensor attached) and fitting of the HMD (with the head-motion tracking sensor attached). The mouse was then placed in the participant's dominant hand, and he or she was guided in positioning the fingers on the mouse buttons. Initialization and calibration of the HMD display followed, in which the participant was asked confirm stereoscopic viewing. The first trial of each block was experimenter triggered. Subsequent trials were triggered by the participant's button-presses. Once the participant responded in a trial with either a left or right button-press, the search display was removed from view and the fixation crosshair presented for 1 s before the next trial's display appeared on screen. The experimenter's triggering of the first search-trial also signalled the software to start storing the participant's head and hip position coordinates for use in calculating the sway measures described in the data analysis section. Each block of task trials yielded one time series of sway data. Since the total time required for a task block varied as a function of the cognitive task's load (averaging about 72 s and 100 s, respectively, for low and high-load conditions, including ISIs), the corresponding time series of sway data differed in the number of data points. To ensure that the sway measures in all conditions were calculated off the same number of data points, and to minimize exposure of the measures to block-initial transients (that might arise, for example, due to the novelty of the viewing condition), sway data from only the final 60 s of each visual search block was used in calculating the sway measures described in section 3.2.4.

For Experiment 1, data collection was carried out as two, successive sessions, corresponding with two instruction conditions. In the *search-focus condition,* participants were asked to perform the visual search task as quickly as possible without making too many mistakes. In the *dual-focus condition*, participants were told that they should try to minimize their sway as much as possible while performing the search task, with equal emphasis given to the postural and cognitive tasks. The order in which these two sessions were given was counterbalanced across participants, and instruction-order included in the visual search and postural analysis as a between-participants factor (see section 3.2.4). Varying stance (open, closed), number of search items (4-low, 16-high) and instruction (search-focus, dual-focus) gave rise to 8 within-participants experimental conditions. These conditions were randomly counterbalanced. The visual search task's design also contained the target (present, absence) condition. Since target presentation was randomized, the target condition was absent in the design used to analyse the postural sway measures described below (section 3.2.4). There was a 5-minute break between the two instruction sessions, during which the HMD was removed and the participant asked to sit down and re-orient before taking up position for the next session. Participants were given one block of 15 (randomly low and high search-load) practice trials at the beginning of each of two sessions.

In Experiments 2, 4 and 6, participants were instructed to focus on performing quick and accurate visual search. In Experiments 3 and 5, participants were asked to perform quick and accurate search but to also focus on minimizing the amount they swayed, with equal emphases being given to these tasks. For Experiments 2-5, varying stance (open, closed), number of search items (4, 16) and reference frame (coincident, non-coincident) gave rise to 8 within-participants, counterbalanced experimental conditions. As for Experiment 1, the search target factor was also included in the visual search analyses. For Experiment 6, varying search depth (2-D, 3-D), search item number (4, 16) and reference frame (coincident, non-coincident) gave rise to 8 within-participants, counterbalanced experimental conditions. Again, the search conditions were blocked, and the target factor included in the visual search analyses. For Experiments 2-6, the eight counterbalanced experimental conditions were presented as a series of two-block sessions, with a 2-3 minute break between sessions. All participants received one block of 15 (randomly low and high search-load) practice trials presented in the coincident frames condition. For Experiment 6, these practice trials were presented in 2-D only.

For all visual search experiments, participants attended a one-hour long session, during which experimental run-time was no more than 25 minutes. The remainder of the session was reserved for fitting of motion-capture sensors and HMD, instructions, practice trials, rest periods and debriefing. No participant was entered into more than one experiment.

3.2.4 Dependent measures and analyses

Cognitive task performance was assessed using the classic accuracy and response time measures for visual search, calculated separately for target-present and target absent trials. Only correct responses were used in analyses of response times. For Experiment 1, the visual search task was analysed using a 2 (target: present, absent) × 2 (stance: open, closed) × 2 (item number: 4, 16) × 2 (instruction: search-focus, dual-focus) within-participants repeated measures, with independent measures on the between-subjects instruction-order factor (search-focus first, dual-focus first). For Experiments 2-5, the visual search task was analysed using a 2 (target: present, absent) × 2 (stance: open, closed) × 2 (item number: 4, 16) × 2 (frame: coincident, non-coincident) within-participants repeated measures design. For Experiment 6, the visual search task was analysed using a 2 (target: present, absent) × 2 (depth: 2-D, 3-D) × 2 (item number: 4, 16) × 2 (frame: coincident, non-coincident) within-participants repeated measures design.

As mentioned, since each search block contained target-present and target-absent trials in random order, the target condition in the visual search task's design was absent in the design used to analyse the postural sway measures. Postural sway was measured using a moving-window standard deviation (MWsd) of anterior–posterior (AP) and medial–lateral (ML) sway, and the corresponding RMS drift. The MWsd measure (henceforth referred to as STS sway) was calculated by dividing each sway time series (i.e., a posture trial corresponding to task trial) into (1 s) non-overlapping windows of 60 data points each, and then averaging the mean standard deviation across windows [157; 222]. The RMS distance between the means of these (1 s) non-overlapping windows was calculated to produce RMS drift (henceforth LTS sway). A schematic description of the two measures is given in Figure 3-2, and a

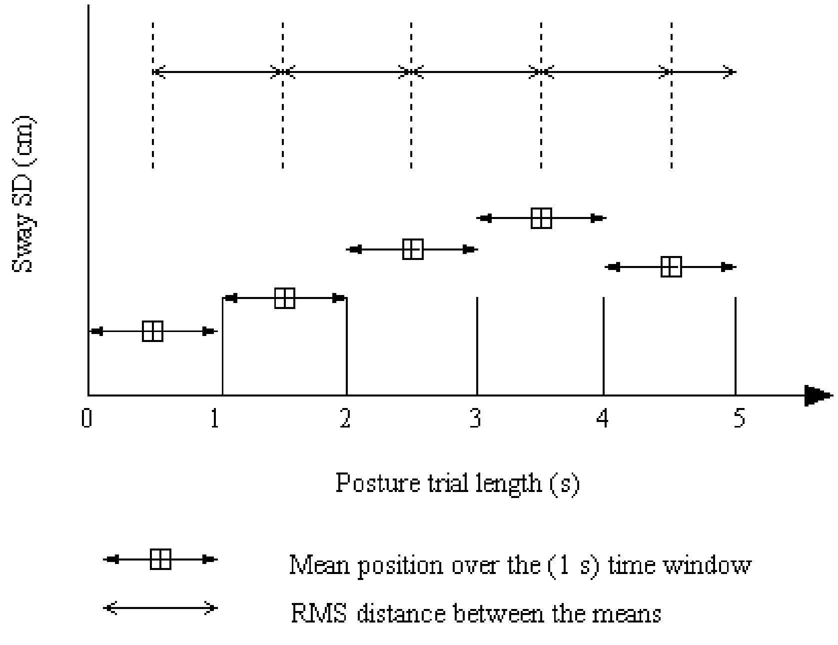

Figure 3-2 Posture sway dependent measures. The short time-scale (STS) measure was computed as the moving-window standard deviation (MWsd) of sway. The long time-scale (LTS) measure was computed as the root mean square (RMS) distance between each of these windowed means.

representative sample of sway data taken from a participant's head-sway data in Experiment 2 shown in Figure 3-3. As discussed in Chapter 2, the two measures were intended to be informative of possible changes in the system's corrections during the trial period under various task-load conditions. The STS and LTS of the hip's motion provided an approximation of the motion of the body's centre of mass, and were therefore used as indicators of the (mechanical) stabilization activities of posture control. The two measures of the head's motion additionally enabled a close look at the changes in the viewpoint of the visual search task that occurred due to postural sway. As such, the head motion data provided an indicator of any task-facilitation activities of posture control.

The data were analysed using repeated-measures analysis of variance (ANOVA). Variable distribution was checked for univariate outliers to reduce the probability of Type I and Type II errors.[7] Regarding assumptions of repeated measures designs, the analysis of variance is known to be robust against violation of univariate normality with respect to Type I error [242] and no transformations were undertaken to normalize the data distributions. Regarding homogeneity of covariance matrices, in cases where data departed significantly from sphericity, the conservative Greenhouse-Geisser correction was applied to the tests of significance, and the corrected significance level reported. The level of significance for main effects and

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[7] Univariate outliers are commonly taken as individuals having z scores =>3 [120]. As defined, the thesis experimental data contained no outliers.

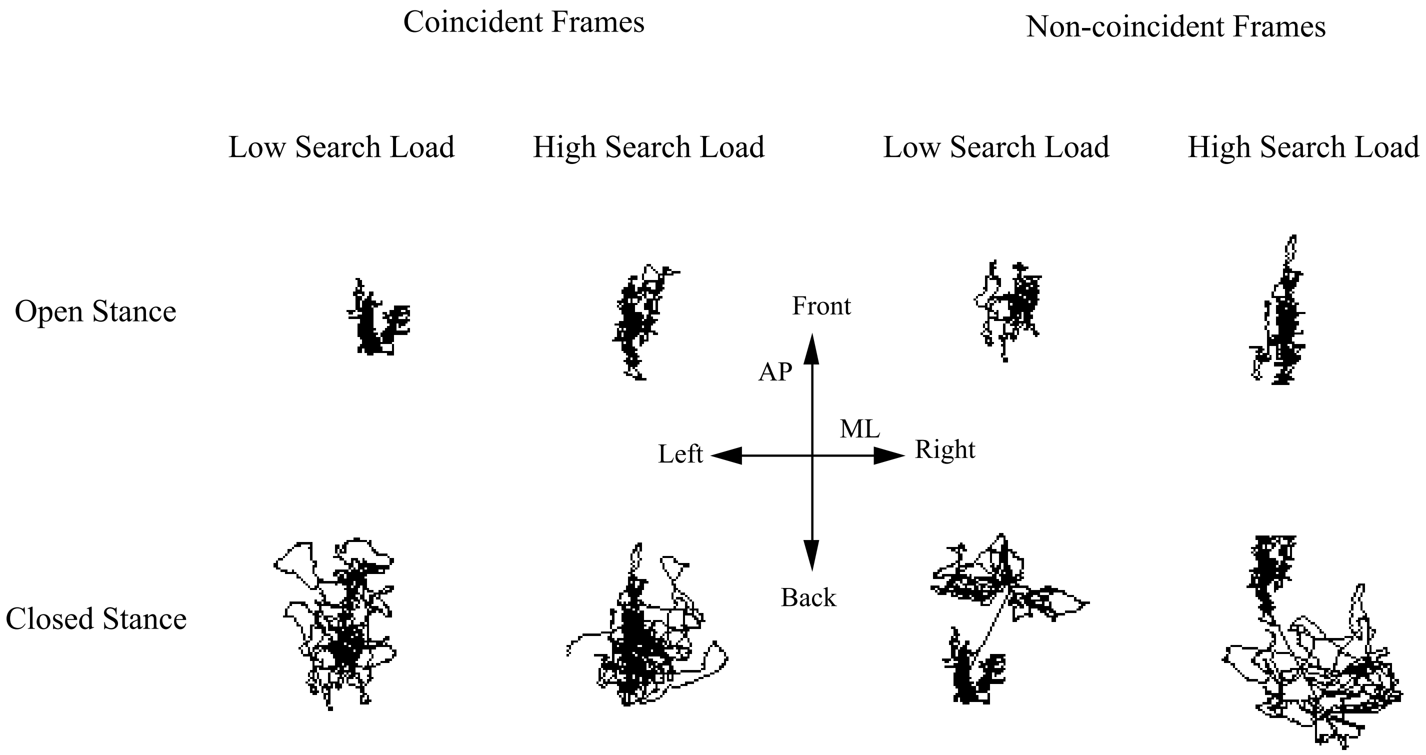

Figure 3-3 A representative participant's head sway data in Experiment 2. The viewpoint is looking down from above. Vertical motions represent anterior-posterior (AP) sway and horizontal motions represent medial-lateral (ML) sway.

interactions was set at $p < .05$. Post hoc tests were performed using simple main effects or else Bonferroni-corrected paired sample *t*-tests [117; 149]. All effects of significance are reported. In keeping with those posture-cognition dual-task studies reporting treatment magnitudes, partial eta (η_p^2) was used to measure effect size. All data analyses were performed using SPSS v.11 software.

3.3 Mental rotation experiment

3.3.1 Apparatus and data collection

General apparatus and data collection was as for visual search Experiments 2-3. In the *coincident frames condition*, the mental rotation objects described below appeared in a world-frame (i.e., the object pair kept their position and orientation in the world-frame). In the *non-coincident frames condition*, the object pair appeared and maintained position-orientation with respect to the observer's head.

3.3.2 Stimuli

The six mental rotation objects consisted of 9 or 10 solid cubes attached face-to-face to form a rigid structure with 3 right-angled elbows. They were given a yellow-brown wood texture (InfiniteReality3 graphics 'lwood3' bit-map), and displayed against a black background. For each object type, a mirror image reversal was generated, creating a total of 12 objects. For each of these, 3 different perspective projections corresponding to a rotation around the axis of the identity object by 50 degree steps (i.e., 50^o, 100^o and 150^o) were generated. To minimize practice effects, the identity object was randomly orientated within each block of trials by a 20^o, -20^o or -40^o angle about the y-axis (the vertical axis about which the object was rotated in depth) or z-axis (the axis parallel to the line of sight about which the object was rotated in the picture plane). These 108 combinations of object axes and rotation and orientation angles were selected so as to ensure that no object part was wholly occluded by another part [232].

3.3.3 Experimental design and procedures

The identity (i.e., reference) object was always presented in the left side of the screen, and the parity/non-parity object always presented on the right side (see Figure 3-4). Each mental rotation block consisted of 10 parity and 10 non-parity trials, randomly presented. Participants were instructed to press the left button of the hand-held mouse if the display in a given trial contained the parity object, and the right button of the mouse if it did not. Participants were instructed to focus on performing quick and accurate mental rotation judgments. As for the visual search experiments, the mental rotation task was performed while standing upright at a location marked with a cross on the laboratory floor. No footwear was worn, and arms were held relaxed by the sides of the body. Postural difficulty was

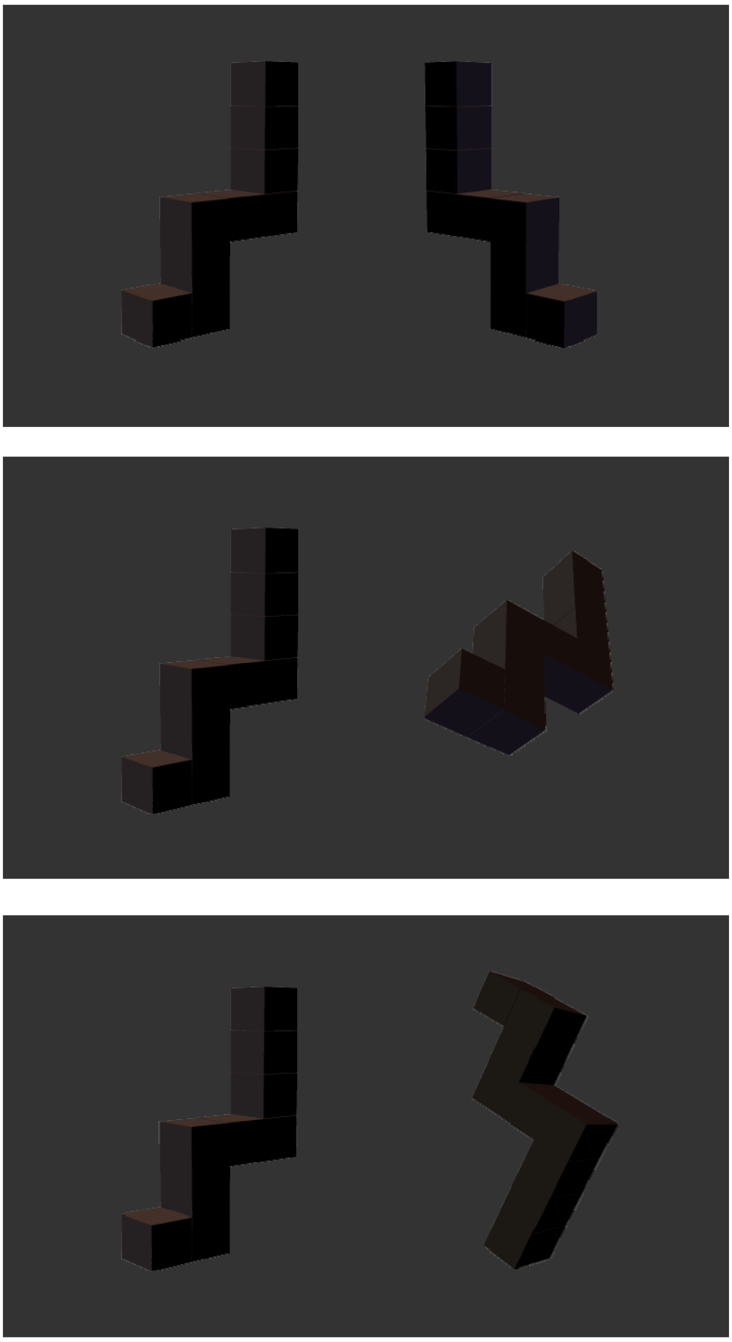

Figure 3-4 Examples of the mental rotation stimuli. The six mental rotation objects consisted of 9 or 10 solid cubes attached face-to-face to form a rigid structure with 3 right-angled elbows. The top panel shows an identity figure (left) and a parity (i.e., same) figure rotated about the y-axis by 100^0 (right). The other panels show the identity figure together with a parity figure rotated about the x-axis by 50^0 (middle panel) and z-axis by 150^0 (lower panel). Block texture and colour are not reproduced here.

manipulated by using open and closed stances, as described for the visual search experiments.

Fitting and calibration of the HMD was as described for the visual search experiments. Recording and storing of data was as for the visual search experiments, only that, due to faster than anticipated response times of some participants for the least difficult (50^{o} rotation, open stance) experimental condition, sway data from only the final 40 s of each mental rotation block was used in calculating the sway measures. Thus, the STS measure was calculated by dividing each sway time series into 1 s non-overlapping windows of 40 data points each, and the RMS distance between the means of these 1 s non-overlapping windows calculated to produce LTS sway.

Varying stance (open, closed), angle displacement size (50^{o}, 100^{o}, 150^{o}) and reference frame (coincident, non-coincident) gave rise to 12 within-participants, experimental conditions. These conditions were randomly counterbalanced. The mental rotation tasks' design also contained the parity/non-parity condition. Since presentation of these was randomized, this condition was absent in the design used to analyse the postural sway measures described below (section 3.3.4). The 12 experimental conditions were presented as a series of three-block sessions, with a 2-3 minute break between each three-block session, during which the HMD was removed and the participant asked to sit down and re-orient before taking up position for the next session. The participants were given one block of 12 practice trials (coincident condition, mixed rotational difficulty) at the beginning of the first block only. Participants attended a one-hour long session, during which experimental run-time was no more than 25 minutes. The remainder of the session was reserved for fitting of motion-capture sensors and HMD, instructions, practice trials, rest periods and debriefing. None of the participants to the metal rotation experiment performed in any of the other thesis experiments.

Before the start of the experimental session, participants were familiarised with the task by viewing and attempting responses to the stimuli presented in 2-D on a computer monitor. Participant feedback from pilot studies revealed that some people performed parity/non-parity judgments based on the direction of a particular leg projection, rather than performing a rotation. For example, an inwards-facing leg on a object would act as a non-parity cue to the outwards-facing leg on the identity object (see [95; 115], for other studies reporting participants' use of non-rotational strategies). This meant that non-parity object rotations about the y-axis were sometimes confused with parity object rotations about the z-axis, leading to incorrect judgments for the y-axis stimuli. As part of the familiarization process, the experimenter alerted the participant's attention to the fact that leg projection was not a reliable cue for correct judgments. No other advice was given as to how judgments should be made.

3.3.4 Dependent measures and analyses

Mental rotation performance was assessed using accuracy and response time measures (correct trials only for RTs) for identity-parity judgments, calculated separately for parity/non-parity trials. The mental rotation task was analysed using a 2 (judgment: parity, non-parity) × 2 (stance: open, closed) × 3 (rotation size: 50^o, 100^o, 150^o) × 2 (frame: coincident, non-coincident) within-participants repeated measures design. Because each mental rotation block contained parity and non-parity trials in random order, the judgment condition in the mental rotation task's design was absent in the design used to analyse the postural sway measures. The sway measures were as described for the visual search experiments.

Chapter 4

Effects of Explicit Sway-Minimization on Posture-Cognition Dual-Tasking

4.1 Introduction

As discussed in Chapter 2, interpreting sway patterns can be problematic when no explicit sway control requirements are specified. Since the dual-task settings employed in the thesis paradigm presented no threat to stance stability, measurable effects might be observed for reference frame (and task-load) conditions depending on the preferred constraints imposed on balance. Close examination of any frame co-registration costs required, therefore, means of cleanly manipulating the resource-sharing settings for the experimental conditions. The experiment described in this chapter was designed to establish such means. Participants were required to stand upright while performing quick and accurate search for a visual target in a conjunction task [259] presented in an immersive environment, under varying postural- and cognitive-load conditions. In one session, henceforth the *search-focus condition*, participants were asked to focus on the visual search task. In a second session, henceforth the *dual-focus condition*, participants were told that the level of body sway was also important, and that they should try to minimize their sway as much as possible. Since the aim of this first experiment was simply to establish whether resource-sharing conditions could be altered according to postural or cognitive task requirements, rather than as a test of the frame co-registration cost hypothesis, the frames for the balance and visual search tasks were designed to always coincide.

While it is a common practice in posture-cognition dual-task research to instruct participants to stand as still as possible, there has been no direct test of postural and cognitive dual-task performance under explicit instruction to control posture. However, there is some evidence to advise that posture sway may increase in dual-task conditions under a sway minimization instruction, relative to a condition in which people are asked simply to focus on the cognitive task. As discussed in Chapter 2, Fearing [82] showed that the release of attention away from balance control and towards a secondary task can enhance postural stability—an outcome accredited to a reduction in balance anxiety following the switching of attention to the secondary task. Similarly, Wulf and colleagues have shown increased postural stability for the adoption of an external focus on the postural task relative to an internal focus of attention [157; 292; 293]. For instance, McNevin and Wulf [157] had participants stand (postural task) while lightly touching a loosely hanging sheet with their fingertips (cognitive task). Participants were either asked to minimize movements of the finger (internal focus with respect to the postural task) or to minimize movements of the sheet (external focus). Both instruction conditions resulted in increased postural sway, but frequency of responding (examined as Fast Fourier Transformation) was greater for the external focus condition compared to internal focus and baseline conditions. Increased postural frequency was taken to indicate increased constraints on (and so greater control over) the body's degrees of freedom [256], and to thus reflect improved balance responses under external focus conditions and compromised balance response under internal focus conditions (see [218], for similar theoretical treatment).[8] Similarly, other work [292] has demonstrated that, compared to internal focus on a cognitive task (focus on the *hands* holding a pole horizontally), external focus on the cognitive task (focus on the *pole*) results in increased cognitive task performance (as well as improved balance control).

From a resource-competition perspective, adding an instruction to minimize sway should increase the load of the postural component by drawing resources into

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[8] McNevin and Wulf's research was based on a study by Riley and colleagues [222], who sought to demonstrate the use (minimization) of posture sway to facilitate a suprapostural task (minimization of sheet movement). McNevin and Wulf set out to establish whether the reduced sway accompanying improved suprapostural task performance observed by Riley et al. was due, not to deliberate use of posture sway to facilitate suprapostural task performance, but to greater reflexive or automatic posture control when attention was prioritized towards the suprapostural task. It can be argued, however, that both the internal focus (minimize finger contact) and external focus (minimize sheet movement) instructions introduced by McNevin and Wulf in fact directed participants attention to the control of the suprapostural task. In this sense, McNevin and Wulf's study cannot be authoritatively considered as a direct test of postural and suprapostural performance in the same dual-task condition under explicit posture focus instructions.

minimizing sway. The precise effects seen on postural or cognitive performance would depend in turn on the available margin for sway reduction with respect to postural or cognitive task difficulty conditions. As discussed in Chapter 2, the postural control system normally allows movements of the body's COG during quiet standing within certain limits [54]. In the dual-task situation under a low resource load, when only few attentional resources are required, the system may be free to drift to a greater degree than in the situation imposed by more difficult dual-task conditions, under which a sway-minimization instruction would be found to have greater impact (on either postural or cognitive task performance). Thus, if the amount of allowable sway for the postural-cognitive task combination permits room for sway to be further minimized, an instruction to reduce sway may have no measurable effect on cognitive task performance. If, on the other hand, posture control is operating close to the margin of its stability limits, then increasing resource-load through instruction to control sway may lead to posture drift and, possibly, a worsening of cognitive performance.

4.2 Method

General method was given in Chapter 3.

4.2.1 Participants

Twenty-two undergraduate students from the University of Warwick participated in the study, receiving course credit for their participation. They ranged from 18 to 30 years in age, 1.50 to 1.79 m in height, and 48 to 91 kg in weight. All reported normal or corrected-to-normal vision, and none had any history of neurological or balance disorders. All participants were naïve to the purpose of the experiment, and were debriefed in detail only after data collection was completed. A number of participants were familiar with the visual search task, but none had previously encountered the stimuli used in this study, and none had previously participated in a posture control experiment. One participant's data was eliminated from all analyses due to measurement errors during sway data collection.

4.3 Results

4.3.1 Instruction-order

To establish whether instruction-order had any carryover effects on the instruction factor, data for the visual search and sway measures were entered into an analysis of variance (ANOVA) with independent measures on the between-participants instruction-order factor (search-focus first, dual-focus first) and with repeated measures on the within-participants factors. The only significant effect involving the instruction factor was an instruction × instruction-order interaction for visual search response time, $F_{(1,19)} = 6.612$, $p < .05$, $\eta_p^2 = .258$; RT was always faster under the instruction condition that participants received second. As this performance improvement was not significantly different for the counterbalanced instruction-order groups, it can be concluded that this was a straightforward practice effect, well known in the visual search literature [282]. Since there were no other significant effects involving the instruction-order and instruction factors, data from both instruction-order conditions were pooled, and all further analyses were carried out with repeated measures on the within-participants factors only.

4.3.2 Visual search

Analysis of variance (ANOVA) was conducted on percent accuracy and response time with repeated measures on target condition (present, absent), instruction (search-focus, dual-focus), search-load (low, high) and stance (open, closed) within-participant factors.

Accuracy. ANOVA showed significant main effects of search-load ($F_{(1, 20)} = 5.412$, $p < .05$, $\eta_p^2 = .213$; accuracy was greater in the low search-load condition), and target

($F_{(1,\ 20)} = 18.824$, $p < .001$, $\eta_p^2 = .485$; accuracy was greater in the target-absent condition). The target × search-load interaction was significant, $F_{(1,\ 20)} = 10.029$, $p < .01$, $\eta_p^2 = .334$; accuracy dropped significantly in the target-present condition as search-load increased ($F_{(1,\ 20)} = 13.743$, $p < .05$, $\eta_p^2 = .389$), but there were no significant differences in the corresponding target-absent conditions (see Figure 4-1, top panel).

Response Time. There were significant main effects of search-load ($F_{(1,\ 20)} = 212.876$, $p < .05$, $\eta_p^2 = .914$; RT was faster in the low search-load condition), and target ($F_{(1,\ 20)} = 171.636$, $p < .001$, $\eta_p^2 = .896$; RT was faster in the target-present condition). The target × search-load interaction (see Figure 4-1, bottom panel) was significant, $F_{(1,\ 20)} = 107.068$, $p < .001$, $\eta_p^2 = .843$; RT rose more sharply in the target-absent than the target-present condition as search-load increased ($t_{(20)} = 10.347$, $p < .001$). The average search slope was 0.027 s/item on target-present trials, and 0.052 s/item on target-absent trials. There was a significant search-load × instruction × stance interaction, $F_{(1,\ 20)} = 5.746$, $p < .05$, $\eta_p^2 = .223$. The mean differences of interest occurred in the high search-load condition (see Figure 4-2). Under the search-focus instruction, RT was numerically (but not significantly) lower in closed than in open stance. Under the dual-focus condition, however, RT was significantly higher in the more difficult, closed stance, $F_{(1,\ 20)} = 4.321$, $p < .05$.

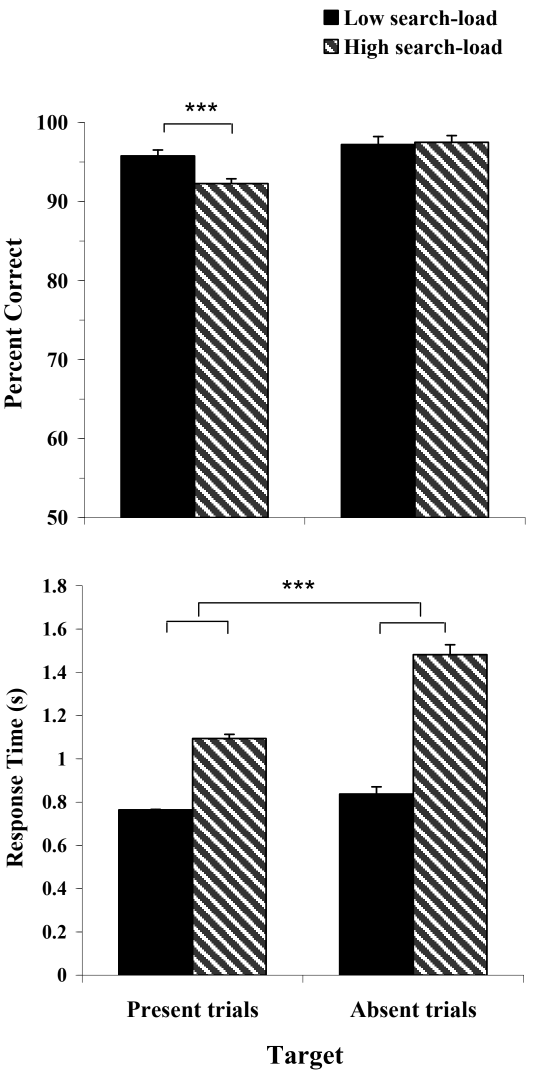

Figure 4-1 Percent accuracy (top panel) and response time (bottom panel) for low and high search-load as a function of target (present-absent) in Experiment 1. Error bars show standard errors of the means. Asterisks denote effects of interest statistically significant at the $p < .001$ level.

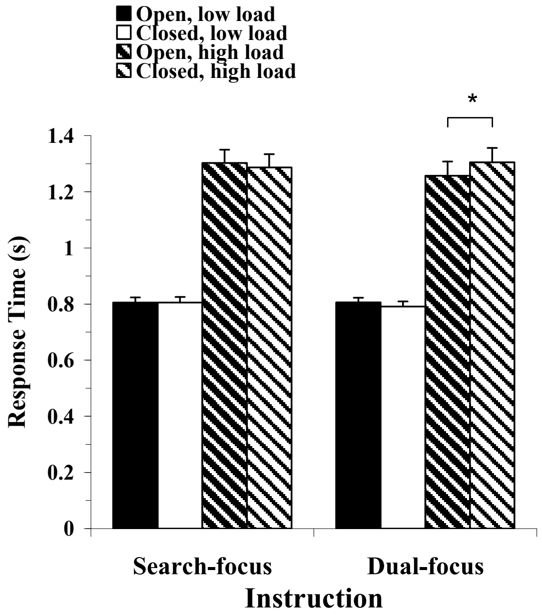

Figure 4-2 Response time for postural and cognitive task-load conditions as a function of instruction in Experiment 1. Error bars show standard errors of the means. Asterisk denotes effect of interest statistically significant at the $p < .05$ level.

4.3.3 Postural sway

Repeated measures ANOVA was conducted on the shorter time-scale (STS) and longer-time-scale (LTS) measures, separately for ML and AP sway, with instruction (search-focus, dual-focus), search-load (low, high) and stance (open, closed) as within-participant factors.

On the STS measure, considering ML sway first (see Figure 4-3, top-left panel), ANOVA showed significant main effects of search-load ($F_{(1, 20)} = 8.022$, $p = .01$, $\eta^2_p = .286$; STS-ML sway was greater in the higher search-load condition), and stance ($F_{(1, 20)} = 148.305$, $p < .001$, $\eta^2_p = .881$; STS-ML sway was greater in the closed stance). There was a significant main effect of instruction, $F_{(1, 20)} = 6.438$, $p < .05$, $\eta^2_p = .244$; STS-ML sway was greater in the search-focus ($M = .027$, $SE = .001$) than the dual-focus condition ($M = .023$, $SE = .001$). On the STS-AP measure (see Figure 4-3, top-right panel), there were significant main effects of search-load ($F_{(1, 20)} = 10.525$, $p < .05$; $\eta^2_p = .345$; STS-AP sway was greater in the higher search-load condition), and stance ($F_{(1, 20)} = 24.119$, $p < .001$, $\eta^2_p = .547$; STS-AP sway was greater in the closed stance). The main effect of instruction was significant, $F_{(1, 20)} = 7.021$, $p < .05$, $\eta^2_p = .260$: STS-AP sway was greater in the search-focus ($M = .077$, $SE = .005$) than the dual-focus condition ($M = .072$, $SE = .005$).

Turning to the LTS drift measure, considering LTS-ML sway first (see Figure 4-3, bottom-left panel), there were significant main effects of search-load ($F_{(1, 20)} = 6.262$, $p < .05$, $\eta^2_p = .238$; LTS-ML sway was greater in the higher search-load condition), and stance ($F_{(1, 20)} = 168.300$, $p < .001$, $\eta^2_p = .894$; LTS-ML sway was greater in the closed stance). On the LTS-AP measure (see Figure 4-3, bottom-right panel), significant main effects were found for search-load ($F_{(1, 20)} = 19.879$, $p < .05$, $\eta^2_p = .498$; LTS-AP sway was greater in the higher search-load condition), and stance ($F_{(1, 20)}$ = 19.446, $p < .001$, η^2_p = .493; LTS-AP sway was greater in the closed stance). The main effect of instruction was significant, $F_{(1, 20)}$ = 6.258, $p < .05$, η^2_p =.238; LTS-AP sway was greater in the search-focus (*M* = .122, *SE* = .004) than the dual-focus condition (*M* = .102, *SE* = .003).

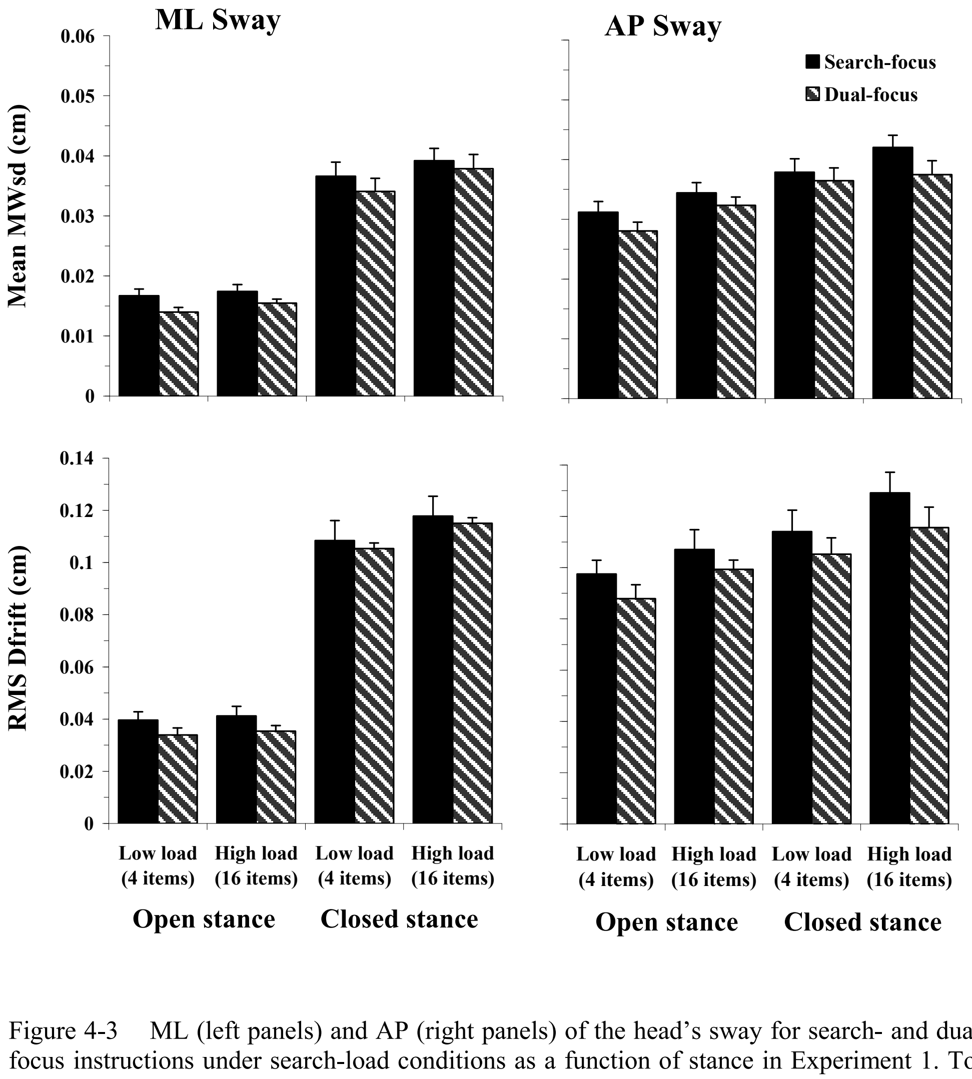

Figure 4-3 ML (left panels) and AP (right panels) of the head's sway for search- and dual-focus instructions under search-load conditions as a function of stance in Experiment 1. Top panels show STS and bottom panels show LTS. Error bars show standard errors of the means.

4.4 Discussion

Before presenting the experimental results in detail it is worth noting that the obtained sway size means are comparable to posture-cognition work [222] using similar measures but applied in non-immersive environment setting. Participants swayed significantly more on the shorter time-scale (STS) measure in both ML and AP directions when they stood in the more difficult closed stance, thereby replicating previous work [162] using this dual-task paradigm. However, based on STS results, participants succeeded in reducing their sway when they were asked to do so. They also demonstrated lesser sway in the dual-focus than the search-focus condition on the LTS measures, although this effect was significant only in the AP direction. Overall, these results strongly suggest that participants were able to prioritize resources towards control of posture, contradictory to the notion that allocation of attention towards balance negatively interferes with automatised processes .

On both measured time-scales, participants swayed more when they performed the more demanding search task. This increased sway with increasing cognitive task-load has been interpreted as a resource-competition, destabilization effect due to increased visual complexity [162]. Searching a display with a larger number of items requires a greater number of precise eye fixations and movements per trial, thereby adding to cognitive-load, and to a resource-draw away from the balancing task [162]. This issue is considered further in the discussion to Experiment 2.

On the characteristics of the visual search task, the approximate 2:1 ratio of the search slopes (0.027 s/item on target-present trials, and 0.052 s/item on target-absent trials) is consistent with a self-terminating process for visual search. This process has been explained in terms of serial search, in which individual items are located one-at-a-time [257-260; 281; 284], or as a parallel, limited-capacity process, in which all items are located simultaneously but at lower individual rate [153; 231]. On serial accounts, the linear increase in RTs for absent trials is rationalized by applying the logic that, on present trials, the search target may be the first or last item checked in the display, or any fall anywhere between these extremes. In which case, random search for a target requires on average only half of the display items to be checked if the target is present, but requires all items in the display to be checked if the target is absent [282]. On a parallel account, the linear increase in RTs is explained in terms of a capacity limitation in reallocating attention to the target following parallel detection of all the display items [37]. Regardless of the precise explanation as to the cause of search efficiency, both accounts agree that increasing set size increases task-load [282]. Following Mitra [162], the fact that the slopes obtained in the present study are at the top end of the typical range for visual search [282; 283] confirms that the task was attentionally demanding, and that the manipulation of the number of search items effected a significant change search-load.

The finding of greater number of errors on present trials than on absent trials under increased search-load, as in this experiment, is a common effect found in visual search. The most straightforward explanation is that people are more cautious when responding to target present than target absent trials [271]. While accuracy in target-present trials dropped significantly in the high search-load condition (92.6 percent correct trials), this amounted to an average of only 1.74 failures to detect the target in the 20 search trials in that condition. This suggests that participants were able to devote an adequate amount of cognitive effort to the search task.

A notable finding was that the pattern of response times for stance and search-load manipulations significantly differed between the two instruction conditions. The effect of interest occurred only under high search-load conditions. In the absence of instruction to minimize sway, people tended to search faster (at a minimal cost to accuracy) when performing in closed rather than open stance (see Figure 4-2). Under dual-focus conditions, however, search was significantly slower when performed in closed stance. The former effect was found to be significant in Mitra [162] and was explained either as participants having felt pressurized when performing search in a difficult stance under visually-restrictive immersive environment conditions, or that the increased amplitude sway in the more difficult stance aided the perceptual detection of sway, allowing resources to be devoted to the search task. Following which, the shift from increment to decrement in task-performance under the dual-focus conditions of the present study might be explained as the sway-detection advantage of closed stance under search-only instruction conditions as being attenuated or eliminated through a reduction in sway. An alternative explanation is provided by the adaptive resource sharing hypothesis [162;

163]. This considers that the sharing or partitioning of resources between postural-cognitive task components is adaptively constrained by the availability of autonomous and facilitatory control patterns according to the level of resource-load, as well as the availability of perceptual support for postural and cognitive task components and the precision requirements of the cognitive task [163]. On this view, the experimental data of the present study might be explained as facilitatory operations (i.e., faster search) being no longer afforded when joint emphasis was given to performing the postural and cognitive tasks, owing to a resource-draw away from the search-task and into sway-minimization.

In conclusion, the experiment's findings confirmed the suitability of the experimental paradigm to the investigation of the frame co-registration cost hypothesis. Firstly, the results replicated the findings of Mitra [162] in showing that the dual-task combination of upright stance and conjunction visual-search can generate postural effects of cognitive task-load in healthy, young adults. Secondly, the results confirmed the sway minimization instruction as an effective experimental means of altering the resource-setting between task-components, so supporting the role of this manipulation in the examination of any frame co-registration costs on respective task components. That work begins in Chapter 5.

Chapter 5

Postural Costs of Performing Cognitive Tasks in Non-Coincident Reference Frames: The Basic Effect

5.1 Introduction

As introduced, the present series of experiments tests the frame co-registration cost hypothesis using a dual-task in which participants maintained unperturbed upright stance (postural component) while performing a visual conjunction search task (cognitive component) that was presented in 3-D space, either entirely in the same spatial reference frame as the postural task (coincident frames condition), or entirely in a different reference frame that maintained a dynamically complex relationship with the postural task's reference frame (non-coincident frames condition). The load of postural and cognitive task components was manipulated, and performance in postural and cognitive components observed as the relationship between the world and task frames was altered. It was predicted that having to perform the search task in a non-coincident reference frame would have a negative impact on postural stability, as measured by an increased level of sway, over and above the expected negative impact of search-load on postural stability. In Experiment 2 participants were instructed to focus on the visual search task, but in Experiment 3 they were instructed to also minimize sway.

5.2 Experiment 2

5.2.1 Method

General method was given in Chapter 3.

5.2.1.1 Participants

Twenty-four undergraduate students at the University of Warwick participated in the study, receiving course credit for their participation. They ranged from 18 to 20 years in age, 1.57 to 1.88 m in height, and 52 to 76 kg in weight. All reported normal or corrected-to-normal vision, and none had any history of neurological or balance disorders. All participants were naïve to the purpose of the experiment, and were debriefed in detail only after data collection was completed. A number of participants were familiar with the visual search task, but none had previously encountered the stimuli used in this study, and none had previously participated in a posture control experiment. Two participants' data were eliminated from all analyses due to measurement errors during sway data collection.

5.2.2 Results

5.2.2.1 Visual Search

Analysis of variance (ANOVA) was conducted on percent accuracy and response time with repeated measures on target condition (present, absent), frame (coincident, non-coincident), search-load (low, high) and stance (open, closed) within-participants factors.

Accuracy. ANOVA showed significant main effects of search-load ($F_{(1, 21)} = 22.655, p < .001, \eta^2_p = .519$; accuracy was greater in the low search-load condition), and target ($F_{(1, 21)} = 30.448, p < .001, \eta^2_p = .592$; accuracy was greater in the target-absent condition). The target × search-load interaction was significant, $F_{(1, 21)} = 171.636, p < .001, \eta^2_p = .890$; accuracy on target-present trials dropped significantly as search-load increased ($F_{(1, 21)} = 23.292, p < .001, \eta^2_p = .526$), but there were no significant differences in the corresponding target-absent conditions (see Figure 5-1, top panel). There was a significant target × frame × stance interaction, $F_{(1, 21)} = 4.345, p = .05, \eta^2_p = .171$; on target-absent trials, accuracy was significantly lower in non-coincident frames than coincident frames when participants stood in closed stance (see Figure 5-2), $F_{(1, 21)} = 5.923, p < .05, \eta^2_p = .220$.

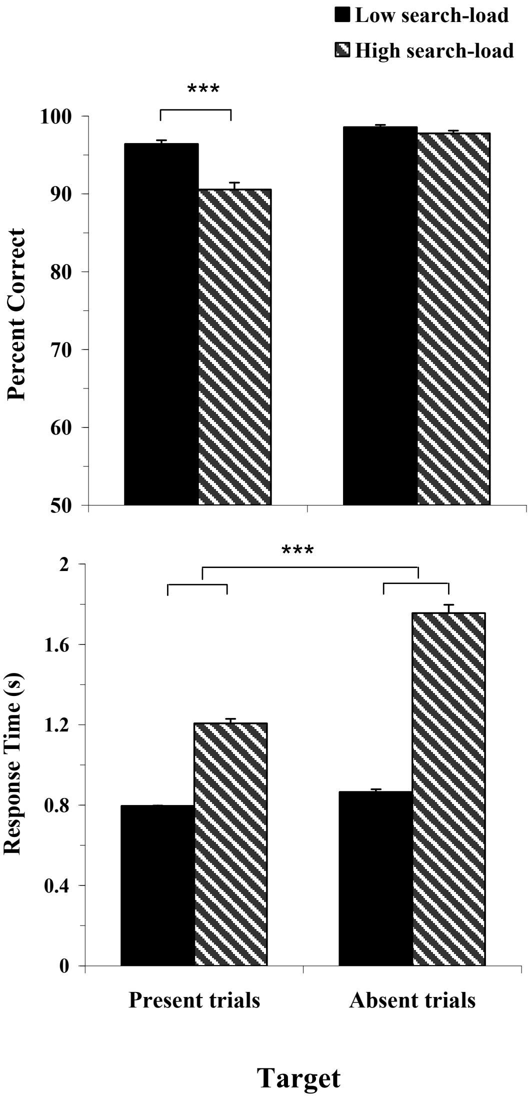

Figure 5-1 Percent accuracy (top panel) and response time (bottom panel) for low and high search-load as a function of target (present-absent) in Experiment 2. Error bars indicate standard error of the means. Asterisks denote effects of interest statistically significant at the $p < .001$ level.

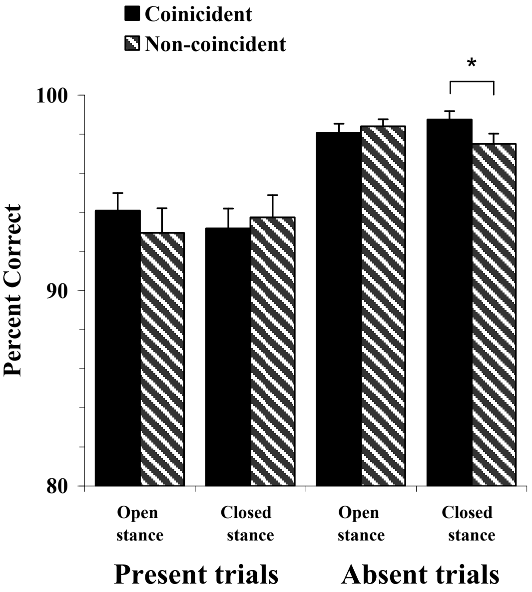

Figure 5-2 Percent accuracy for coincident and non-coincident frames under postural difficulty conditions as a function of target (present-absent) in Experiment 2. Error bars indicate standard error. Asterisk denotes effect of interest statistically significant at the $p < .05$ level.

Response Time. There were significant main effects of search-load ($F_{(1,\ 21)}$ = 256.801, $p < .001$, $\eta^2_p = .924$; RT was faster in the low search-load condition), and target ($F_{(1,\ 21)}$ = 115.794, $p < .001$, $\eta^2_p = .846$; RT was faster in the target-present condition). The target × search-load interaction (see Figure 5-1, bottom panel) was significant, $F_{(1,\ 21)}$ = 77.879, $p < .001$, $\eta^2_p = .788$; RT rose more sharply on target-absent than on the target-present trials as search-load increased, $t_{(21)}$ = 8.825, $p <$ .001. The average search slope was 0.034 s/item on target-present trials, and 0.074 s/item on target-absent trials. A significant frame × search-load interaction ($F_{(1,\ 21)}$ =

5.302, $p < .05$, $\eta_p^2 = .202$) indicated that RT was significantly higher in non-coincident than coincident frames under high search-load conditions, $F_{(1, 21)} = 5.093$, $p < .05$ (see Figure 5-3).

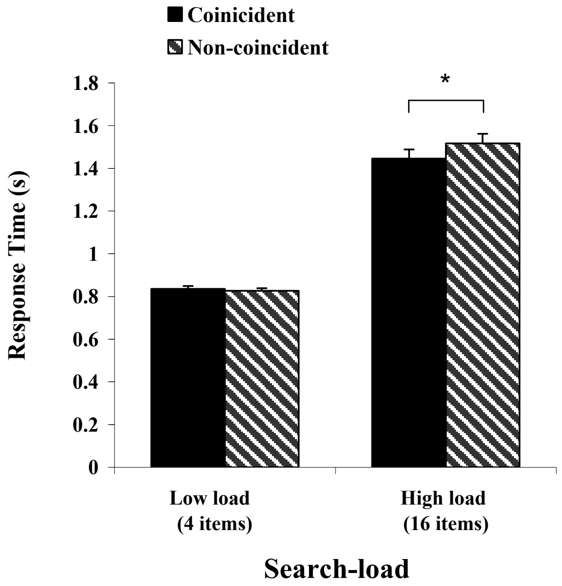

Figure 5-3 Response time for coincident and non-coincident frames as a function of search-load in Experiment 2. Error bars show standard errors of the means. Asterisk denotes effect of interest statistically significant at the $p < .05$ level.

5.2.2.2 Postural Sway

Repeated measures ANOVA was conducted on the shorter time-scale (STS) and longer-time-scale (LTS) measures, separately for ML and AP sway, with frame (coincident, non-coincident), search-load (low, high) and stance (open, closed) as within-participants factors.

Head sway. On the STS measure and for ML sway (see Figure 5-4, top-left panel), significant main effects were found for search-load ($F_{(1, 21)} = 17.756, p < .001, \eta_p^2 = .458$; STS-ML sway was greater in the higher search-load condition), and stance ($F_{(1, 21)} = 189.991, p < .001, \eta_p^2 = .900$; STS-ML sway was greater in the closed stance). On the STS measure of AP sway (see Figure 5-4, top-right panel), again there were significant main effects of search-load ($F_{(1, 21)} = 17.544, p < .001, \eta_p^2 = .455$; STS-AP sway was greater in the higher search-load condition), and stance ($F_{(1, 21)} = 22.028, p < .001, \eta_p^2 = .512$; STS-AP sway was greater in the closed stance). Notably, there was a significant frame × search-load interaction, $F_{(1, 21)} = 5.894, p < .05, \eta_p^2 = .219$; STS-AP sway rose significantly in the non-coincident frames condition as search-load increased ($F_{(1, 21)} = 18.023, p < .001, \eta_p^2 = .462$), but there were no significant differences in the corresponding coincident frames conditions (see Figure 5-5).

Turning to the LTS measure, considering LTS-ML sway first (see Figure 5-4, bottom-left panel), there were significant main effects of search-load ($F_{(1, 21)} = 12.432, p < .01, \eta_p^2 = .372$; LTS-ML sway was greater in the higher search-load condition), and stance ($F_{(1, 21)} = 191.499, p < .001, \eta_p^2 = .901$; LTS-ML sway was greater in the closed stance). On the LTS-AP measure (see Figure 5-4, bottom-right panel), significant main effects were found for search-load ($F_{(1, 21)} = 23.189, p <.001, \eta_p^2 = .525$; LTS-AP sway was greater in the higher search-load condition), and stance ($F_{(1, 21)} = 13.021$, $p < .001$, $\eta^2_p = .383$; LTS-AP sway was greater in the closed stance).

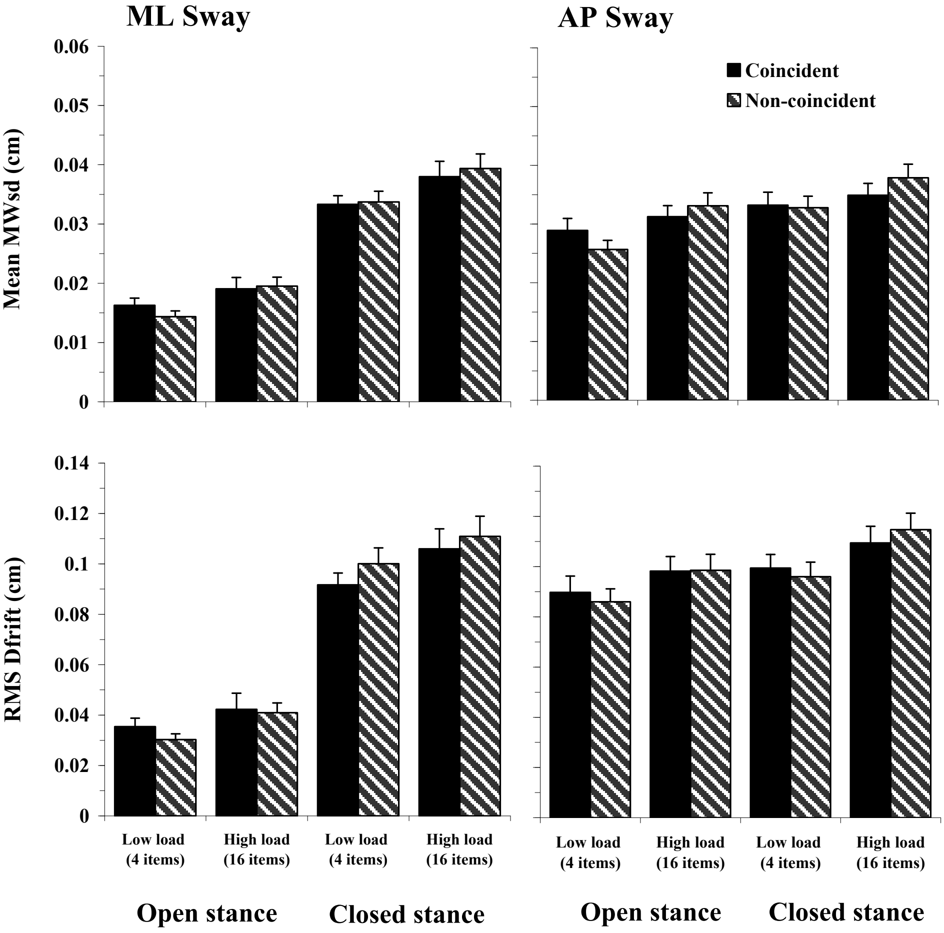

Figure 5-4 ML (left panels) and AP (right panels) on the head's sway for coincident and non-coincident frames under search-load conditions as a function of stance in Experiment 2. Top panels show STS and bottom panels show LTS. Error bars indicate standard error of the means.

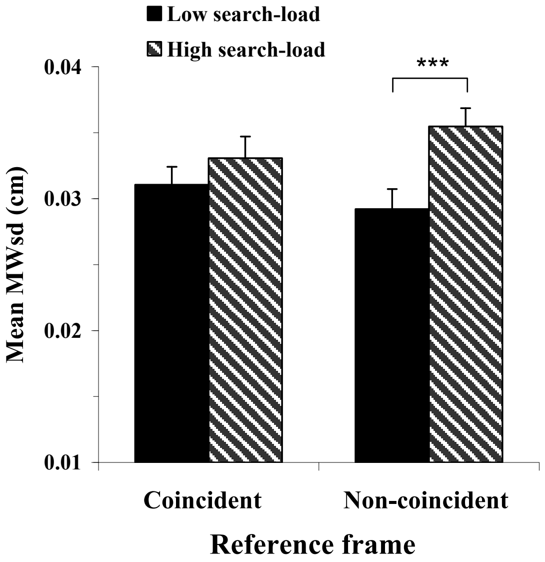

Figure 5-5 STS-AP of the head's sway for low and high search-load as a function of reference frame in Experiment 2. Error bars show standard errors of the means. Asterisks denote effect of interest statistically significant at the $p < .001$ level.

Hip sway. On the STS measure and for ML sway (see Figure 5-6, top-left panel), ANOVA showed significant main effects of search-load ($F_{(1, 21)} = 8.960$, $p < .01$, $\eta_p^2 = .299$; STS-ML sway was greater in the higher search-load condition), and stance ($F_{(1, 21)} = 146.939$, $p < .001$, $\eta_p^2 = .875$; STS-ML sway was greater in the closed stance). On the STS-AP measure (see Figure 5-6, top-right panel), significant main effects were found for search-load ($F_{(1, 21)} = 12.273$, $p < .01$, $\eta_p^2 = .369$; STS-AP sway was greater in the higher search-load condition), and stance ($F_{(1, 21)} = 44.348$, $p < .001$, $\eta_p^2 = .679$; STS-AP sway was greater in the closed stance).

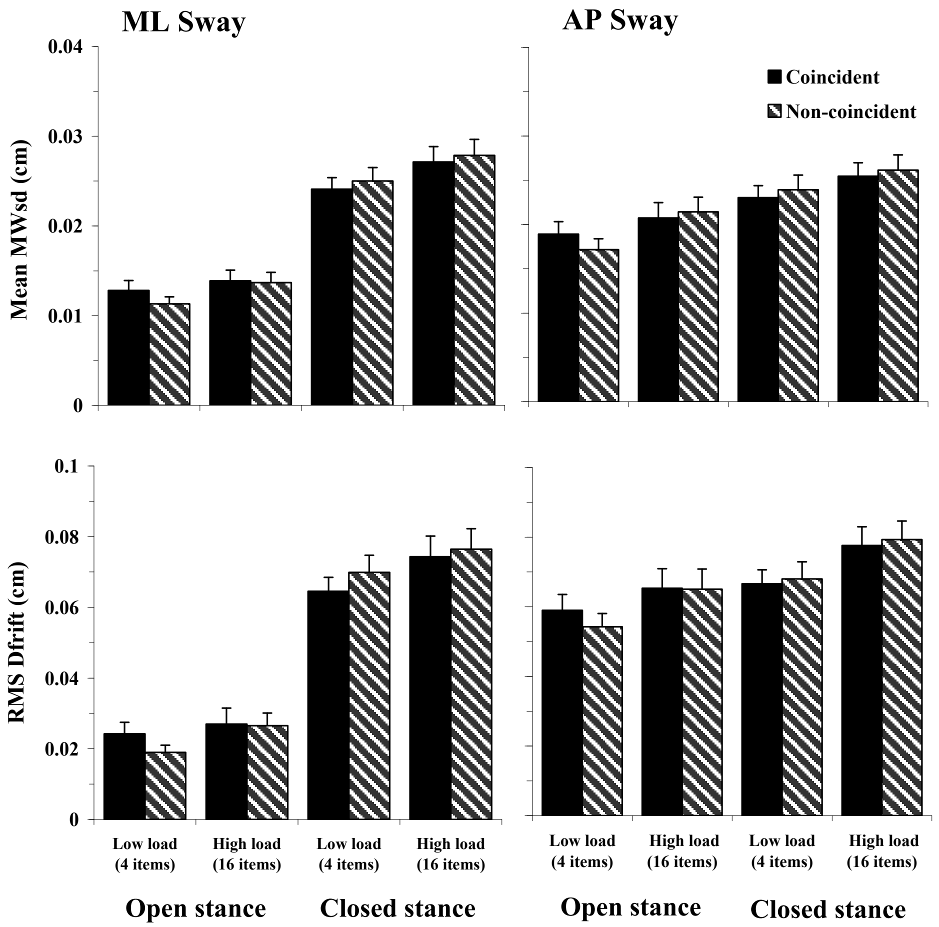

Figure 5-6 ML (left panels) and AP (right panels) on the hip's sway for coincident and non-coincident frames under search-load conditions as a function of stance in Experiment 2. Top panels show STS and bottom panels show LTS. Error bars indicate standard error of the means.

Turning to the LTS measure for the hip segment, and considering LTS-ML sway first (see Figure 5-6, bottom-left panel), there were significant main effects of search-load ($F_{(1,\,21)} = 7.976$, $p = .01$, $\eta_p^2 = .275$; LTS-ML sway was greater in the higher search-load condition), and stance ($F_{(1,\,21)} = 174.067$, $p < .001$, $\eta_p^2 = .892$;

LTS-ML sway was greater in the closed stance). On the LTS-AP measure (see Figure 5-6, bottom-right panel), significant differences were found for search-load ($F_{(1,\ 21)} = 17.724$, $p < .001$, $\eta_p^2 = .458$; LTS-AP sway was greater in the higher search-load condition), and stance ($F_{(1,\ 21)} = 18.214$, $p < .001$, $\eta_p^2 = .464$; LTS-AP sway was greater in the closed stance).

5.2.3 Discussion

On the visual search task, the search slope in the target-present condition (0.034 s/item) was once more approximately half of the slope found in the target-absent condition (0.074 s/item). The slopes were greater (by about 20 percent in both target conditions) than those obtained by Mitra [162] using the same task-combination, instruction set, and frame manipulations, but there the visual search display was presented as a planar surface. By contrast, the present experiment required search to be performed across multiple depth planes, necessitating binocular convergence movements to attain and re-attain fixation on the search items. This may have added to the cognitive load of the search task. The issues that may arise out of the presence or absence of depth variation across search items are addressed specifically in Experiment 6. Note that, despite the effortful search, a high level of accuracy was achieved across all conditions, with the lowest accuracy score (92.6% in the target-present, high-load condition) amounting to an average of only 1.48 failures to detect the target in the 20 search trials in that condition. This suggests that participants were able to devote an adequate amount of cognitive effort to the search task.

In the postural component of the dual-task, participants swayed more, as could be anticipated, in both AP and ML directions on all measures when they stood in closed stance as opposed to open stance. Also, participants swayed more when they performed the more demanding search task. In earlier discussion, it was noted that this increase in sway with increasing visual search task-load has been interpreted by as a destabilization of posture control due to increasing number of eye fixation and movements required per trial under increased cognitive task-load [162]. Mitra [162] only recorded head segment movement. It could be argued that the larger number of eye movements required in the high-load search conditions might have led to inadvertently larger head movements that may be misconstrued as increased postural sway. In the present study, however, the increase in sway with increasing search-load was observed on the hip segment as well. This provides support for the interpretation that increasing the cognitive task-load led to an observable level of mechanical destabilization of stance due to an increased draw on shared resources by the more demanding search task.

The most important result for present purposes was the effect of the frame coincidence manipulation on the STS measure of the head's AP sway. Participants swayed more in the non-coincident frames condition as search-load increased. This result is consistent with the hypothesis that the need to maintain the world- and task-frames in register in the non-coincident frames condition draws on resources required for postural control. The task of interpreting the differential effect on posture control of performing search in the two frame conditions is complicated, however, by the fact that search performance differed across frame conditions. There was a significant interaction between frame coincidence and search-load on search RT showing that increased search-load had a greater negative impact on task performance when the search task had to be performed in non-coincident frames. Also, search accuracy suffered under closed stance in the non-coincident frames condition on target-absent trials (although the interpretation of results from target-absent trials in visual search is known to be problematic, see [51]). These results suggest that the search task itself may have been less demanding in the coincident frames condition. It is possible, for example, that the availability of visual information such as radial optic flow and motion parallax in the coincident frames condition made it easier for participants to determine the relative locations of search items in the display. This in turn may have made search less resource-intensive than in the non-coincident frames condition. If so, the detrimental effect of non-coincident frames on postural stability could have been the result of a greater resource draw due to increased search task difficulty rather than due to non-coincidence of reference frames per se.

A related concern is that the interpretation of added resource draw due to frame non-coincidence depends on the implicit assumption that participants were in fact trying to minimize their sway in all experimental conditions. As discussed in Chapter 4, the posture control system may not always need to keep sway at a minimum in order to maintain stability, especially when stance is unperturbed, and the COM is well within the stability boundary. Since the visual search task required multiple, precise eye fixations, a posture control strategy for facilitating search ought to have minimized viewpoint movement (i.e., reduced sway), and more so under greater search-load [162]. The opposite pattern observed in the present experiment showed, however, that participants either did not try to reduce their sway to this end, or they tried but did not succeed. Since participants did not receive any specific instructions with respect to the postural component (except for the obvious requirement of maintaining upright stance), there was no way of disambiguating between an increase in sway due to a relative inability to devote resources to controlling sway (due to added frame co-registration costs), as opposed to simply de-emphasizing sway control when the cognitive task was in a non-coincident frame. In other words, participants many have heavily prioritized the search task, and did not try to control their sway beyond keeping within the stability boundary. This discrepancy in performance criteria is addressed in Experiment 3.

5.3 Experiment 3

In the present experiment, participants were explicitly instructed to control the level of body sway while performing the visual search task. If the detrimental effects of search-load on sway in Experiment 2 were indeed due to common resources being drawn away from posture control, it can be expected on basis of the results to

Experiment 1 that explicitly asking participants to maintain adequate resourcing of sway minimization in all conditions would stem the flow of resources out of posture control (i.e., stem those resources that, in the absence of a sway-minimization instruction, would otherwise be allocated to visual search). Accordingly, it was expected to observe a relative decrement in search performance and an attenuation or elimination of the frame manipulation’s effect on the search task.

5.3.1 Method

Method was as described for Experiment 2, but with the following differences.

5.3.1.1 Participants

Twenty-one undergraduate students from the University of Warwick participated in the study, receiving course credit for their participation. They ranged from 18 to 36 years in age, 1.60 to 1.83 m in height, and 55 to 72 kg in weight. All reported had normal or corrected-to-normal vision, and none had any history of neurological or balance disorders. All participants were naïve to the purpose of the experiment, and were debriefed in detail only after data collection was completed. A number of participants were familiar with the visual search task, but none had previously encountered the stimuli used in this study, and none had previously participated in a posture control experiment. Two participants’ data were eliminated from all analyses due to measurement errors during sway data collection.

5.3.1.2 Experimental procedures

The only change to procedures was that participants were told that the level of body sway while standing upright was important to the study, and that they should try to minimize their sway as much as possible while performing the visual search task as well as they could, with equal emphasis given to both tasks.

5.3.2 Results

5.3.2.1 Visual Search

Analysis of variance (ANOVA) was conducted on percent accuracy and RT with repeated measures on target condition (present, absent), frame (coincident, non-coincident), search-load (low, high) and stance (open, closed) within-participant factors.

Accuracy. ANOVA showed significant main effects of search-load ($F_{(1,\ 18)}$ = 21.812, $p < .001$, η^2_p = .548; accuracy was greater in the low search-load condition), and target ($F_{(1,\ 18)}$ = 33.852, $p < .001$, η^2_p = .653; accuracy was greater in the target-absent condition). The target × search-load interaction was significant, $F_{(1,\ 18)}$ = 32.419, $p < .001$, η^2_p = .643; accuracy dropped significantly on target-present trials as search-load increased ($F_{(1, 18)} = 5.472$, $p < .001$, $\eta^2_p = .234$), but there were no significant differences in the corresponding target-absent conditions.

Response Time. There were significant main effects of search-load ($F_{(1, 18)} = 128.110$, $p < .001$, $\eta^2_p = .877$; RT was faster in the low search-load condition), and target ($F_{(1, 18)} = 111.114$, $p < .001$, $\eta^2_p = .861$; RT was faster in the target-present condition). The search-load × target interaction was significant, $F_{(1, 18)} = 83.931$, $p < .001$, $\eta^2_p = .823$; RT rose more sharply on absent trials than on present trials as search-load increased, $t_{(18)} = 9.161$, $p < .001$. The average search slope was 0.028 s/item on target-present trials, and 0.061 s/item on target-absent trials.

5.3.2.2 Postural sway

Repeated measures ANOVA was conducted on the shorter time-scale (STS) and longer-time-scale (LTS) measures, separately for ML and AP sway, with frame (coincident, non-coincident), search-load (low, high) and stance (open, closed) as within-participants factors.

Head sway. On the STS measure and for ML sway, ANOVA showed significant main effects of search-load ($F_{(1, 18)} = 16.055$, $p = .001$, $\eta^2_p = .471$; STS-ML sway was greater in the higher search-load condition), and stance ($F_{(1, 18)} = 171.115$, $p < .001$, $\eta^2_p = .905$; STS-ML sway was greater in the closed stance). There was a significant stance × search-load interaction, $F_{(1, 18)} = 4.590$, $p < .05$, $\eta_p^2 = .203$; STS-ML sway rose more sharply in closed stance than in open stance as search-load increased, $t_{(18)} = 3.313$, $p < .01$. There was a significant search-load × frame × stance interaction (see Figure 5-7), $F_{(1, 18)} = 6.964$, $p <. 05$, $\eta_p^2 = .279$; as search-load increased, STS-ML sway significantly increased in the coincident frames condition under open stance ($F_{(1, 18)} = 12.423$, $p <. 01$, $\eta_p^2 = .402$), and significantly increased in the non-coincident frames condition under closed stance ($F_{(1, 18)} = 23.740$, $p <. 001$, $\eta_p^2 = .569$). On the STS measure of the AP sway, there were significant main effects of search-load ($F_{(1, 18)} = 16.000$, $p = .001$, $\eta_p^2 = .471$; STS-AP sway was greater in the higher search-load condition), and stance ($F_{(1, 18)} = 34.082$, $p < .001$, $\eta_p^2 = .654$; STS-AP sway was greater in the closed stance).

Turning to the LTS measure of head sway, considering LTS-ML first, there were significant main effects of search-load ($F_{(1, 18)} = 12.513$, $p = .01$, $\eta_p^2 = .410$; LTS-ML sway was greater in the higher search-load condition), and stance ($F_{(1, 18)} = 270.137$, $p < .001$, $\eta_p^2 = .938$; LTS-ML sway was greater in the closed stance). The stance × search-load interaction was significant, $F_{(1, 18)} = 6.945$, $p < .05$, $\eta_p^2 = .278$; LTS-ML sway increased significantly in closed stance as search-load increased ($F_{(1, 18)} = 14.218$, $p = .001$, $\eta_p^2 = .429$), but there were no significant differences in the corresponding open stance conditions. On the LTS-AP measure of the head segment, significant main effects were found for search-load ($F_{(1, 18)} = 13.088$, $p <$

.01, η_p^2 = .421; LTS-AP sway was greater in the higher search-load condition), and stance ($F_{(1,\ 18)}$ = 10.194, p = .05, η_p^2 = .362; LTS-AP sway was greater in the closed stance).

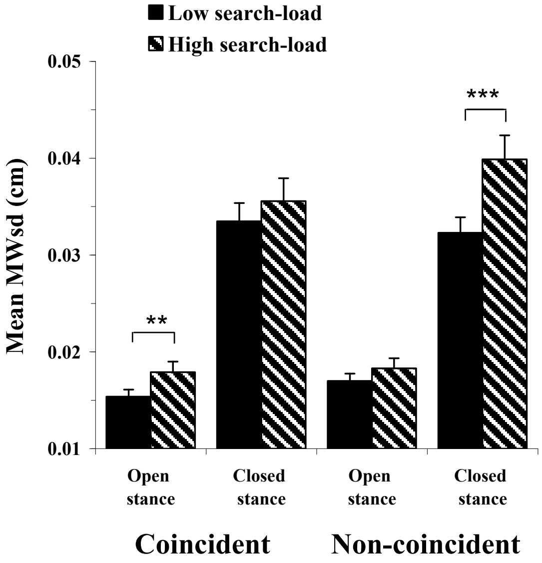

Figure 5-7 STS-ML of the head's sway for low and high search-load under postural difficulty conditions as function of reference frame in Experiment 3. Error bars indicate standard error of the means. Asterisks denote effects of interest statistically significant at $p < .01$ (**) and $p < .001$ (***) level.

Hip sway. On STS measure and for ML sway, ANOVA showed significant main effects of search-load ($F_{(1,\ 18)}$ = 13.384, p < .01, η_p^2 = .162; STS-ML sway was greater in the higher search-load condition), and stance ($F_{(1,\ 18)}$ = 137.601, p < .001, η_p^2 = .884; STS-ML sway was greater in the closed stance). The search-load × stance interaction was significant, $F_{(1,\ 18)}$ = 7.136, p < .05, η_p^2 = .284; STS-ML sway increased significantly in closed stance as search-load increased ($F_{(1,\ 18)}$ = 13.534, p < .01, η^2_p = .415), but there were no significant differences in the corresponding open stance conditions. On the STS measure of the hip segment's AP sway, there were significant main effects of search-load ($F_{(1,\ 18)}$ = 23.239, p < .001, η^2_p = .564; STS-AP sway was greater in the higher search-load condition), and stance ($F_{(1,\ 18)}$ = 27.411, p < .001, η^2_p = .604; STS-AP sway was greater in the closed stance). The main effect of frame was significant, $F_{(1,\ 18)}$ = 4.654, p < .05, η^2_p = .205; STS-AP sway was greater in the non-coincident (*M* = .021, *SE* = .006) than the coincident frames condition (*M* = .21, *SE* = .006).

On the LTS measure of hip sway, considering LTS-ML sway first, there were significant main effects of search-load ($F_{(1,\ 18)}$ = 9.797, p < .01, η^2_p = .352; LTS-ML sway was greater in the higher search-load condition), and stance ($F_{(1,18}$ = 245.983, p < .001, η^2_p = .932; LTS-ML sway was greater in the closed stance). Again, the search-load × stance interaction was significant, $F_{(1,\ 18)}$ = 9.694, p < .01, η^2_p = .350; LTS-ML sway increased significantly in closed stance as search-load increased ($F_{(1,\ 18)}$ = 14.128, p = .01, η^2_p = .440), but there were no significant differences in the corresponding open stance conditions. On the LTS-AP measure, significant main effects were found for search-load ($F_{(1,\ 18)}$ = 20.378, p < .001, η^2_p = .531; LTS-AP sway was greater in the higher search-load condition), and stance ($F_{(1,\ 18)}$ = 15.574, p = .001, η^2_p = .464; LTS-AP sway was greater in the closed stance). The main effect of frame was significant, $F_{(1,\ 18)} = 11.563$, $p < .01$, $\eta_p^2 = .391$; LTS-AP sway was greater in the non-coincident ($M = .060$, $SE = .002$) than the coincident frames condition ($M = .055$, $SE = .002$).

5.3.2.3 Effects of instruction to control sway

To assess the effects of adding an instruction to control sway in Experiment 3, data from Experiments 2 and 3 were analysed together with instruction (search-focus, dual-focus) added as a between-participants factor. Significant effects involving the instruction factor were as follows.

Visual Search. On the accuracy measure, the target × search-load × instruction interaction was significant, $F_{(1,\ 39)} = 6.213$, $p < .05$, $\eta_p^2 = .137$; accuracy on absent trials under low search-load was lower in the dual-focus than the search-focus condition, $F_{(1,\ 39)} = 4.893$, $p < .05$, $\eta_p^2 = .111$. On the RT measure, there was a significant target × search-load × frame × instruction interaction, $F_{(1,\ 39)} = 4.563$, $p < .05$, $\eta_p^2 = .105$; in the search-focus condition, RT on present trials under high search-load was lower in coincident than non-coincident frames, $F_{(1,\ 39)} = 6.439$, $p < .01$), but there were no significant differences in the corresponding dual-focus conditions.

Postural Sway. There were no significant effects involving the between-participants instruction factor on any of the head segment measures. Considering the hip segment, the only significant effect involving the instruction factor was a significant frame × instruction interaction on the LTS-AP measure, $F_{(1,39)} = 4.654$, $p < .05$, $\eta_p^2 = .185$; LTS-AP sway greater in non-coincident than coincident frames under the dual-focus instruction ($F_{(1,\ 39} = 10.845$, $p < .01$), but there were no significant differences in the corresponding search-focus conditions.

5.3.3 Discussion

Considering cognitive task performance first, the search slopes obtained in the present experiment (0.028 s/item in target-present and 0.061 s/item in the target-absent conditions) were notably shallower than those obtained in Experiment 2 (0.034 s/item in target-present and 0.074 s/item in the target-absent conditions). This speeding-up of search-task performance appears to have been at only minimal cost to accuracy (an average of 1.76 failures to detect the target out of 20 trials in the least accurate target-present, high-load condition, as opposed to 1.48 failures in Experiment 2). Despite this apparent strategic tightening of search slopes, however, the sway-minimization instruction appears to have left no room for those effects of frame coincidence on search accuracy and RT found in Experiment 2, as confirmed by the between-participants analyses.

With respect to performance in the postural task component, the results of the present experiment mirrored those of Experiment 2 in that participants swayed more, as expected, in the more demanding closed stance condition, and they also swayed more when the visual search-load was greater. As in Experiment 2, these effects were significant across the short and long time-scale measures of both head and hip sway, and along both the AP and ML axes. Compared to the single interaction on the head segment involving the frame manipulation in Experiment 2, requiring participants to control sway in the present experiment elicited a more pronounced postural performance deficit when the cognitive task was in a non-coincident frame. On both the long and short time-scale measures, hip sway in the AP direction increased in the non-coincident frames condition, indicating clearly that performing the search task in the non-coincident frame reduced the mechanical stability of stance. These postural costs are rendered more interpretable as effects of frame coincidence, moreover, by the absence of frame costs in cognitive task performance.

On the STS-ML sway measure for the head segment, performing the more difficult visual search resulted in increased sway in coincident frames under open stance, and increased sway in non-coincident frames under closed stance. An interpretation of this result is that in order to maintain performance on the search task people allowed themselves to sway more in the more secure open stance (not an uncommon finding in healthy young adults operating under low-load conditions, [62; 151; 159]). This loosening of sway, however, seems not to have been possible in the non-coincident frames condition, due to added cost of having to keep task-frames in register.

There was only a single significant effect along the postural measures indicating reduced sway under instruction to do so. Though this result (on the hip's segment LTS-AP measure) appears to suggest that while participants did not, on the whole, succeed in deliberate sway reduction under the given dual-task setting, the numerical trends across all the measures was towards reduced sway under the combined instruction. It is worth noting that the sway reduction on the hip's LTS-AP sway under the dual-focus instruction was significantly greater in the coincident frames condition. One explanation, in keeping with the thesis hypothesis, is that no frame co-registration costs were associated with the coincident frames condition and, therefore, more shared resources could be allocated to reducing the level of sway. Note also, that this effect was achieved when people had to perform search under high search-load and under closed stance. Thus, the postural control effects observed in the non-coincident frames condition were over and above resource costs that could be attributable to component task loads.

An alternative explanation for the observed postural control effects in non-coincident frames could arise from the fact that the search display in the coincident frames condition potentially offered optic flow for use by the participant in reducing sway. In this condition, the 3-D visual search display maintained its position in the world-frame as the participant's viewpoint moved (in the world-frame) due to body sway. Thus, the participant's sway generated radial optic flow and motion parallax, both known to be potentially useful in controlling postural sway [11; 38]. In contrast, in the non-coincident frames condition, as the participant swayed, the search display maintained its position relative to the participant's viewpoint and, therefore, did not generate any optical information about the level of sway to aid sway reduction. It could be argued thus that the relatively lower levels of sway observed in the coincident frames condition were not due to the absence of frame co-registration costs, as hypothesized, but due to the difference in visual information available for posture control in the two conditions. Other work using the present paradigm [162] produced no indication that the posture control system does, or is able to, use the optical structure of a visual search display to modify levels of body sway. As noted however, the search display in that work did not contain depth variation. To eliminate the presence or absence of optic flow as a source of frame effects, the next series of experiments (4-6) employ a variant of the present experiment in which both the coincident and non-coincident frames conditions offer identical visual information of potential use in posture control.

Chapter 6

Postural Costs of Performing Cognitive Tasks in Non-Coincident Reference Frames: Split Frames

6.1 Introduction

The purpose of the present series of experiments was to introduce a variant of the dual-task arrangement that eliminated the optic flow performance differences between the coincident and non-coincident frames conditions for the previous series. In the present series, the basic dual-task was identical in all respects to that of Experiments 2 and 3 except in the way the coincident and non-coincident frames conditions were implemented. In Experiments 2 and 3, the entire search display either appeared in the world-frame or in a task-frame anchored to the participant's swaying head. In contrast, in the present experiments, the search items were equally distributed between the world-frame and the (head-anchored) task-frame, based on item colour. In the coincident frames condition, all the blue search items ('A' distractors and the 'H' target) appeared in, and maintained position-orientation with respect to, the world-frame, while the green items ('H' distractors) appeared in, and maintained position-orientation with respect to, the participant's swaying head. In the non-coincident frames condition, the green items appeared in, and maintained position-orientation with respect to, the world-frame, while the blue search items, including the search target, appeared in, and maintained position-orientation with respect to, the participant's swaying head. Thus, the coincident and non-coincident frame designations were based on which frame contained the blue 'H' search target.

These frame-condition designations were based on the evidence that item- or location-based pre-attentive grouping of visual-field elements can allow nearly parallel search within groupings [75; 76]. Segmentation by grouping in visual search has been shown for a variety of conjunction searches (depth-location [97], depth-colour [169], colour-orientation [253], colour-location [119]), including motion-static combinations [155; 156; 271]. In light of this evidence, the present variant of the search task offered two types of pre-attentive grouping of search displays. First, the green and blue item groups could be segmented by colour, and second, they could also be segmented by motion. The latter possibility arose from the optical consequences of the swaying viewpoint of the standing participant. In the coincident-frames condition, the blue group (containing the target in the target-present trials) maintained its position in the world-frame while the green group moved with the viewpoint. The blue group, therefore, generated radial optic flow as a result of the participant's AP sway, and the blue and green groups also generated motion parallax by virtue of their relative optical motion due to viewpoint motion (particularly along the ML axis). In the non-coincident frames condition, the optical dynamics were identical except that it was the green group that maintained its position in the world-frame and generated radial optic flow as the viewpoint swayed.

The parallax generated across groups was the same as in the coincident-frames condition. Thus, the search displays in both frame conditions generated exactly the same optic flow characteristics as a result of the participant's swaying viewpoint, the only difference being the swapping of blue and green colour groups.

Though the optical characteristics of the two frame conditions were now exactly matched, their load implications in combination with a postural task component could still be differentiated in terms of the frame co-registration hypothesis. Once the green items were segmented from the blue items (via grouping by colour or motion or both), search for the target would occur among the blue items. In the coincident frames, this segmentation would eliminate all the (green) items appearing in the task-frame, leaving the search to continue among the remaining blue items in the world-frame. In each search trial, beyond the point of this segmentation, there remained no need for the task-frame to be kept in register with the world-frame (and both the search and task components could continue in the world-frame). In the non-coincident frames condition, however, segmentation would eliminate all the (green) items appearing in the world-frame, leaving the search to continue among blue items in the task-frame. The task-frame would therefore need to be kept in register with the world-frame throughout each search trial. The frame co-registration hypothesis would therefore generate the same prediction as before—the non-coincident frames condition would incur additional frame co-registration costs and place a higher demand on shared resources. In Experiment 4 participants were instructed to focus on the visual search task, but in Experiment 5, they were instructed to also minimize sway.

6.2 Experiment 4

6.2.1 Method

Method was as described for Experiment 2, with the following differences.

6.2.1.1 Participants

Twenty-six undergraduates and postgraduates from the University of Warwick participated in the study, receiving payment for their participation. They ranged from 19 to 32 years in age, 1.55 to 1.92 m in height, and 48 to 73 kg in weight. All reported normal or corrected-to-normal vision, and none had any history of neurological or balance disorders. All participants were naïve to the purpose of the experiment, and were debriefed in detail only after data collection was completed. Several participants had previously participated in a posture control experiment, and several were familiar with the visual search task, but none had performed the type of task combination (i.e., posture control and visual search) used in this study.

6.2.2.1 Apparatus, experimental design and procedures

All arrangements were identical to those in Experiment 2 except for the search display layouts in the two frame conditions. As introduced above, in the coincident frames condition, all the green search items were mounted on the display such that they maintained their position with respect to the participants' (swaying) viewpoint. All blue items were mounted such that they maintained their position in the world-frame. Phenomenologically, the swaying participants saw the blue items remain static in the world while the green items moved with their viewpoint. In the non-coincident frames condition, it was exactly the other way around. Participants were given exactly the same instructions as in Experiment 2.

6.2.2 Results

6.2.2.1 Visual search

Analysis of variance (ANOVA) was conducted on percent accuracy and response time with repeated measures on target condition (present, absent), frame (coincident, non-coincident), search-load (low, high) and stance (open, closed) within-participants factors.

Accuracy. ANOVA showed significant main effects of search-load ($F_{(1,\ 25)}$ = 51.752, $p < .001$, η^2_p = .674; accuracy was greater in the low search-load condition), and target ($F_{(1,\ 25)}$ = 34.544, $p < .001$, η^2_p = .580; accuracy was greater in the target-absent condition). The target × search-load interaction was significant, $F_{(1,\ 25)}$ = 46.893, $p < .05$, η^2_p = .653; accuracy on target-present trials dropped significantly as search-load increased ($F_{(1,\ 25)}$ = 63.244, $p < .001$, η^2_p = .717), but there were no significant differences in the corresponding target-absent conditions.

Response Time. On the RT measure, there were main effects of search-load ($F_{(1,\ 25)}$ = 230.119, $p < .001$, η^2_p = .902; RT was faster in the low search-load condition), and target ($F_{(1,\ 25)}$ = 193.400, $p < .001$, η^2_p = .886; RT was faster in the target-present condition). The target × search-load interaction was significant, $F_{(1,\ 25)}$ = 141.705, $p < .001$, η^2_p = .850; RT rose more sharply on target-absent than on target-present trials as search-load increased, $t_{(25)}$ = 11.904, $p < .001$. The average search slope was 0.031 s/item on target-present trials, and 0.076 s/item on target-absent trials.

6.2.2.2 Postural sway

Repeated measures ANOVA was conducted on the shorter time-scale (STS) and longer-time-scale (LTS) measures, separately for ML and AP sway, with frame (coincident, non-coincident), search-load (low, high) and stance (open, closed) as within-participants factors.

Head Sway. On the STS measure and for ML sway, the main effect of stance was significant, $F_{(1,25)} = 176.818$, $p < .001$, $\eta_p^2 = .876$; STS-ML sway was greater in the closed stance. On the STS measure of AP sway, there were main effects of search-load ($F_{(1,25)} = 9.463$, $p < .01$, $\eta_p^2 = .275$; STS-AP sway was greater in the higher search-load condition), and stance ($F_{(1,25)} = 16.397$, $p < .001$, $\eta_p^2 = .385$; STS-AP sway was greater in the closed stance). The main effect of frame was significant, $F_{(1,25)} = 5.090$, $p < .05$, $\eta_p^2 = .169$; STS-AP sway was greater in the non-coincident ($M = .032$, $SE = .001$) than the coincident frames condition ($M = .030$, $SE = .001$).

Turning to the LTS measure, considering the head's LTS-ML sway first, the main effect of stance was significant, $F_{(1,25)} = 230.576$, $p < .001$, $\eta_p^2 = .902$; LTS-ML sway was greater in the closed stance. On the LTS-AP measure, the main effect of stance was significant, $F_{(1,25)} = 19.775$, $p < .001$, $\eta_p^2 = .442$; LTS-AP sway was greater in the closed stance. The main effect of frame was marginally significant, $F_{(1,25)} = 4.120$, $p = .053$, $\eta_p^2 = .141$; LTS-AP sway was marginally greater in the non-coincident ($M = .095$, $SE = .003$) than the coincident frames condition ($M = .090$, $SE = .002$).

Hip Sway. On the STS measure of the hip's ML sway, ANOVA showed a main effect of stance, $F_{(1,25)} = 30.794$, $p < .001$, $\eta_p^2 = .552$; STS-ML sway was greater in the closed stance. The main effect of frame was marginally significant, $F_{(1,25)} =$

4.139, p = .053, η_p^2 = .142; STS-ML sway was marginally greater in the non-coincident (M = .025, SE = .002) than the coincident frames condition (M = .019, SE = .001). On the STS measure of the hip's AP sway, the main effect of stance was significant, $F_{(1,\ 25)}$ = 8.154, p < .01, η_p^2 = .246; STS-AP sway was greater in the closed stance. The main effect of frame was also significant, $F_{(1,\ 25)}$ = 7.843, p = .01, η_p^2 = .239; STS-AP sway was greater in the non-coincident (M = .024, SE = .001) than the coincident frames condition (M = .020, SE = .001).

Turning to the LTS measure of hip sway, considering LTS-ML sway first, ANOVA showed a significant main effect of stance, $F_{(1,\ 25)}$ = 163.542, p < .001, η_p^2 = .867; LTS-ML sway was greater in the closed stance. The main effect of frame was significant, $F_{(1,\ 25)}$ = 10.528, p = .01, η_p^2 = .296; LTS-ML sway was greater in the non-coincident (M = .052, SE = .004) than the coincident frames condition (M = .044, SE = .003). On the LTS-AP measure, there was a significant main effect of stance, $F_{(1,\ 25)}$ = 27.99, p < .001, η_p^2 = .528; LTS-AP sway was greater in the closed stance. The main effect of frame was significant, $F_{(1,\ 25)}$ = 11.407, p < .01, η_p^2 = .313; LTS-AP sway was greater in the non-coincident (M = .065, SE = .002) than the coincident frames condition (M = .058, SE = .002).

6.2.3 Discussion

Considering the visual search performance first, the search slopes (0.031 s/item on target-present trials, and 0.076 s/item on target-absent trials) were nearly identical to those obtained in Experiment 2 where, as in the present experiment, there was no explicit instruction to control postural sway. Accuracy was again quite high, with the lowest accuracy score being 90.5% in the target-present, high-load condition (amounting to just less than 2 failures to detect the target out of 20 trials in that condition). These performance measures suggest that the search task spread across two reference frames had similar characteristics to search tasks situated entirely in the world or task-frame. However, unlike in Experiment 2, where the entire search process occurred either in the same frame as the postural task or in a different one, in the present experiment, exactly half the search items always appeared in both reference frames. This symmetry may be why the frame effects on search performance that were observed in Experiment 2 were not found in the present experiment.

With respect to the posture control component, the impact of the visual search task's load was limited to a significant main effect on the STS measure of the head's AP sway. The lesser impact of search-load on posture control in this experiment, as compared to Experiment 2, might be explained as the limited additional effect of increased search-load on the resource draw away from posture control given the already resource-intensive nature of visual search across two reference frames. With respect to the coincident and non-coincident frames manipulation, however, the results were unequivocal. On 4 out of 8 measures of sway performance, participants swayed significantly more (and two further measures, marginally more) when they performed visual search in the non-coincident frames condition. An interpretation of this frame effect in terms of optic flow could now be ruled out, since, by design, the potential for pick-up of radial optic flow and motion parallax was identical in both frame conditions. There was a clear pattern of increased postural sway when the target containing half of the search display appeared in a frame different from the posture control task's world-frame. Since the only difference between the coincident and non-coincident frames conditions was how long, per search trial, the task-frame needed to be kept in register with the world-frame, this experiment provided strong support for the interpretation that postural stability suffered in the non-coincident frames.

6.3 Experiment 5

Experiment 4 provided clear evidence of increased postural sway when the search task required a non-coincident task-frame to be kept in register with the world-frame for longer stretches of time. However, as in the case of Experiment 2, the instructions given to participants did not specify any performance criteria beyond maintaining upright stance. As discussed in the context of Experiments 2 and 3, it is possible that the postural performance results in Experiment 4 were due not to a relative failure to control sway in the non-coincident frames condition, but a de-emphasizing or de-prioritizing of sway control. To test between these two possibilities under the paradigm variant developed for Experiment 4, the present experiment applied the instructions given in Experiment 2 to the conditions of Experiment 4.

6.3.1 Method

Method was as described for Experiment 4, but with the following differences.

6.3.1.1 Participants

Twenty undergraduates and postgraduates from the University of Warwick participated in the study, receiving payment for their participation. They ranged from 19 to 30 years in age, 1.55 to 1.98 m in height, and 49 to 73 kg in weight. All reported normal or corrected-to-normal vision, and none had any history of neurological or balance disorders. All participants were naïve to the purpose of the experiment, and were debriefed in detail only after data collection was completed. Several participants had previously engaged in a posture control experiment, and several were familiar with the visual search task, but none had performed the type of task combination used in this study.

6.3.1.2 Experimental procedures

All procedures were identical to those of Experiment 4 except that participants were told that the level of body sway was important, and that they should try to minimize their sway as much as possible while performing the visual search task as well as they could, with equal emphasis given to both tasks.

6.3.2 Results

6.3.2.1 Visual search

Analysis of variance (ANOVA) was conducted on percent accuracy and response time with repeated measures on target condition (present, absent), frame (coincident, non-coincident), search-load (low, high) and stance (open, closed) within-participants factors.

Accuracy. ANOVA showed significant main effects of search-load ($F_{(1,\ 19)}$ = 18.976, $p < .001$, η^2_p = .500; accuracy was greater in the low search-load condition), and target ($F_{(1,\ 19)}$ = 24.540, $p < .001$, η^2_p = .564; accuracy was greater in the target-absent condition). The target × search-load interaction was significant, $F_{(1,\ 19)}$ = 15.613, $p < .001$, η^2_p = .444; accuracy on target-present trials dropped significantly as search-load increased ($F_{(1,\ 19)}$ = 23.138, $p < .001$, η^2_p = .549), but there were no significant differences in the corresponding target-absent conditions. Overall, accuracy was not as high as in previous experiments. The lowest accuracy was 84.8% in the high-load, target-present condition (amounting to over 3 failures to detect the target out of 20 trials in that condition).

Response Time. There were significant main effects of search-load ($F_{(1,\ 19)}$ = 162.066, $p < .001$, $\eta_p^2 = .895$; RT was faster in the low search-load condition), and target ($F_{(1,\ 19)}$ = 93.389, $p < .001$, $\eta_p^2 = .831$; RT was faster in the target-present condition). The target × search-load interaction was significant, $F_{(1,\ 19)}$ = 72.101, $p < .001$, $\eta_p^2 = .791$; RT rose more sharply on target-absent trials than on target-present trials as search-load increased, $t_{(19)}$ = 8.491, $p < .001$. The average search slope was 0.032 s/item on target-present trials, and 0.073 s/item on target-absent trials.

6.3.2.2 Postural sway

Repeated measures ANOVA was conducted on the shorter time-scale (STS) and longer-time-scale (LTS) measures, separately for ML and AP sway, with frame (coincident, non-coincident), search-load (low, high) and stance (open, closed) as within-participants factors.

Head Sway. On the head segment, main effects of stance were found across all sway measures: STS-ML ($F_{(1,\ 19)}$ = 162.574, $p < .001$, $\eta_p^2 = .895$), STS-AP ($F_{(1,\ 19)}$ =

25.305, $p < .001$, $\eta_p^2 = .571$), LTS-ML ($F_{(1, 19)} = 157.898$, $p < .001$, $\eta_p^2 = .893$), and LTS-AP sway ($F_{(1, 19)} = 48.601$, $p < .001$, $\eta_p^2 = .719$). In all cases, sway was greater in the closed stance. Notably, on the LTS measure of the head's AP sway, the frame × search-load interaction was significant, $F_{(1, 21)} = 6.808$, $p < .05$, $\eta_p^2 = .264$; LTS-AP sway was greater in the non-coincident than the coincident frames condition under high search-load, $F_{(1, 19)} = 6.373$, $p < .05$, $\eta_p^2 = .251$ (see Figure 6-1, left panel).

Hip Sway. On the hip's STS-ML measure, ANOVA showed a significant main effect of stance, $F_{(1, 19)} = 164.321$, $p < .001$, $\eta_p^2 = .896$; STS-ML sway was greater in the closed stance. On the STS-AP measure, there were significant main effects of search-load, $F_{(1, 19)} = 4.947$, $p < .05$, $\eta_p^2 = .207$; STS-AP sway was greater in the higher search-load condition), and stance ($F_{(1, 19)} = 55.995$, $p < .001$, $\eta_p^2 = .747$; STS-AP sway was greater in the closed stance). Turning to the longer time-scale measures, taking ML sway first, the main effect of stance was significant, $F_{(1, 19)} = 199.477$, $p < .001$, $\eta_p^2 = .913$; LTS-ML sway was greater in the closed stance. Also, there was a significant stance × search-load interaction, $F_{(1, 19)} = 7.725$, $p < .05$, $\eta_p^2 = .289$; LTS-ML sway was greater in the closed than the open stance under high search-load, $F_{(1, 19)} = 5.375$, $p < .05$, $\eta_p^2 = .221$. On LTS-AP sway, the main effect of stance was significant, $F_{(1, 19)} = 50.684$, $p < .001$, $\eta_p^2 = .727$; LTS-AP sway was greater in the closed stance. There was a significant frame × search-load interaction, $F_{(1, 19)} = 9.246$, $p < .01$, $\eta_p^2 = .327$; LTS-AP sway fell in the coincident frames condition as search-load increased ($F_{(1,\ 19)} = 4.889$, $p < .05$, $\eta_p^2 = .205$), but there were no significant differences in the corresponding non-coincident frames conditions (see Figure 6-1, right panel). Also, under high search-load, LTS-AP sway was marginally greater in non-coincident than in coincident frames ($F_{(1,\ 19)} = 4.071$, $p = .058$, $\eta_p^2 = .176$).

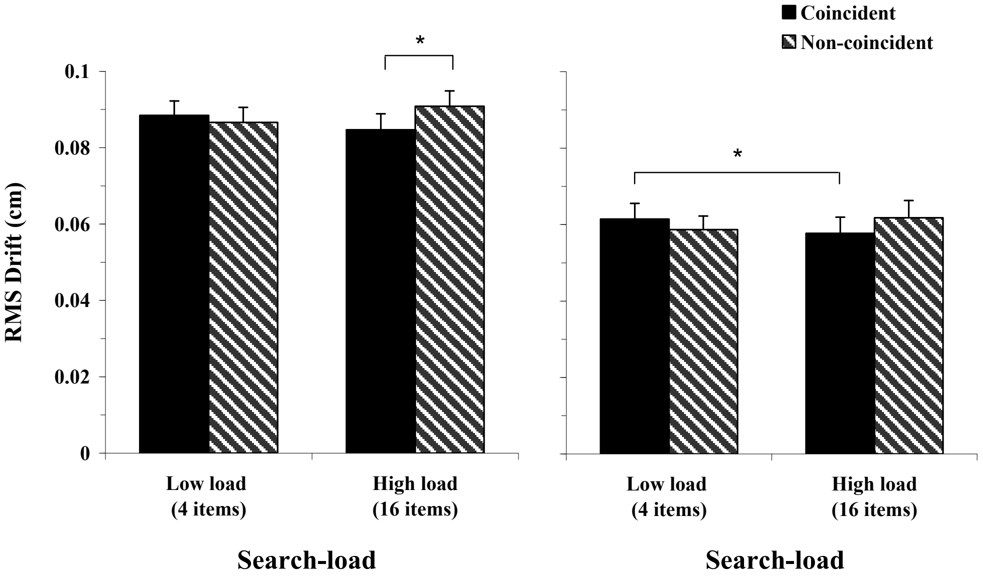

Figure 6-1 LTS-AP of the head (left panel) and hip's sway (right panel) for coincident and non-coincident frames as a function of search-load in Experiment 5. Error bars show standard errors of the means. Asterisk denotes effect of interest statistically significant at the $p < .05$ level.

6.3.2.3 Effects of instruction to control sway

To assess the effects of adding an instruction to control sway in Experiment 5, data from Experiments 4 and 5 were analysed together with instruction (search-focus, dual-focus) added as a between-participants factor. Significant effects involving the instruction factor were as follows.

Visual Search. On the accuracy measure, the main effect of instruction was significant, $F_{(1, 44)} = 7.117$, $p < .05$; $\eta^2_p = .139$; accuracy was lower in the dual-focus condition. The search-load × instruction interaction was significant, $F_{(1, 44)} = 4.847$, $p < .05$, $\eta^2_p = .099$; accuracy fell more sharply with increasing search-load in the dual-focus than the search-focus condition, $F_{(1, 44)} = 7.057$, $p < .05$. The target × stance × instruction interaction was significant, $F_{(1, 44)} = 7.078$, $p < .05$, $\eta^2_p = .139$; accuracy was lower in the dual-focus condition under closed stance on present trials ($F_{(1, 44)} = 6.972$, $p < .05$) and under open stance on absent trials ($F_{(1, 44)} = 6.518$, $p < .05$), as compared to these conditions under the search-only instruction. On RT, the target × stance × instruction interaction was significant, $F_{(1, 44)} = 7.074$, $p < .05$, $\eta^2_p = .137$; dual-focus response time was significantly greater under closed stance than open stance on absent trials ($F_{(1, 44)} = 8.169$, $p < .01$), but there were no significant differences in the corresponding search-focus conditions.

Postural Sway. Considering the head segment first, on the STS-AP measure, there was a significant search-load × instruction interaction, $F_{(1, 44)} = 8.317$, $p < .01$, $\eta^2_p = .159$; STS-AP sway rose significantly in the search-focus instruction condition as search-load increased ($F_{(1, 44)} = 5.090$, $p < .05$), but there were no significant differences in the corresponding dual-focus conditions. There were no other significant effects involving the instruction factor on the head measures.

Considering the hip segment measure next, on the STS-ML measure, there was a significant load × stance × instruction interaction, $F_{(1,\ 44)} = 4.105$, $p < .05$, $\eta_p^2 = .085$); in the search-focus instruction condition, STS-ML sway was greater in non-coincident than coincident frames during closed stance and under low search-load ($F_{(1,\ 44)} = 6.628$, $p < .05$), but there were no significant differences in the corresponding dual-focus conditions. On the STS-AP measure, the frame × instruction interaction was significant, $F_{(1,\ 44)} = 4.341$, $p < .05$, $\eta_p^2 = .090$; in the search-focus instruction condition, sway was significantly greater in the non-coincident than the coincident frames condition ($F_{(1,\ 44)} = 6.093$, $p < .05$), but there were no significant differences in the corresponding dual-focus conditions.

On the longer time-scale measures of the hip segment, on ML sway, a significant frame × instruction interaction ($F_{(1,\ 44)} = 8.403$, $p < .01$, $\eta_p^2 = .160$) indicated that LTS-ML sway was significantly greater in non-coincident than coincident frames under the search-focus instruction ($F_{(1,\ 44)} = 14.362$, $p < .001$), but that there were no significant differences in the corresponding dual-focus conditions. Also on the LTS-ML measure, the search-load × stance × instruction interaction was significant, $F_{(1,\ 44)} = 7.780$, $p < .01$, $\eta_p^2 = .150$. Under open stance, LTS-ML sway tended to be greater in the dual-focus condition under low search-load, but greater in the search-focus condition under high search-load. In the closed stance condition, LTS-ML sway tended to be greater in the search-focus condition under low search-load, but greater in the dual-focus condition under high search-load. On the LTS-AP measure, the frame × instruction interaction was significant, $F_{(1,\ 44)} = 5.173$, $p < .01$, $\eta^2_p = .149$; LTS-AP sway was significantly greater in non-coincident than coincident frames under the search-focus instruction ($F_{(1,\ 44)} = 14.635$, $p < .001$), but there were no significant differences in the corresponding dual-focus conditions.

In summary, the between-participants analysis of Experiments 4 and 5 showed a drop in search performance under dual-focus conditions, and a pattern of frame effects from Experiment 4 being eliminated in Experiment 5 when resources were reserved for minimizing sway.

6.3.3 Discussion

The results of Experiment 5 differed from those of Experiment 4 in ways dissimilar to the differences between results of Experiments 2 and 3. Considering visual search performance first, the search slopes obtained here were nearly identical to those of Experiment 4, indicating that participants maintained a similar overall level of resourcing for the search task in terms of speed (whereas slopes in Experiment 3 were flatter than in Experiment 2). As confirmed in the between-participants analysis, however, adding the explicit instruction to control sway led to a sizeable drop in search accuracy compared to Experiment 3. The between-participants analysis also showed that the drop in accuracy under the dual-focus instruction was greater when search-load was high or when participants were performing in the more demanding closed stance (on present trials). Dual-focus instruction also produced longer RTs in the closed stance condition (on absent trials). These results are consistent with a performance drop due to a resource draw away from search and into deliberate sway minimization.

Considering postural sway results next, on the LTS-AP measure for the head segment, sway increased in the non-coincident frames condition as search-load increased. This occurred in spite of explicit instruction to control sway, and so can be interpreted as an indication of added load in the non-coincident frames condition. As shown in Figure 6-1, there was a trend towards sway reduction with increasing search-load when the target appeared in the coincident frames condition. A similar pattern of results was obtained for the LTS-AP sway of the hip segment. Here, the sway reduction in the coincident frames under high search-load condition was significant, while there was a trend towards increased sway in the corresponding non-coincident frames condition. It is possible that the optically denser search display in the high search-load condition helped participants minimize their sway. However, despite identical optical characteristics of the search displays in both frame conditions, participants did not succeed in similarly reducing sway when the target appeared in the non-coincident task-frame. The simplest interpretation of these effects is that, despite explicit sway minimization instruction, sway control remained less well resourced in the non-coincident frames condition.

Taken together, the deterioration of search performance and attenuation of frame and load effects on posture control were consistent with the frame co-registration cost hypothesis. As in the previous experiments, having to perform the search task in a reference frame that was non-coincident with the posture control task's world-frame again generated an added resource draw away from posture control. This additional resource draw could be partially counteracted by reserving resources for sway minimization, but only at the expense of decrements in task performance.

6.4 Experiment 6

Throughout Experiments 2 to 5, a 3-D version of the visual search task was used that differed from the 2-D task in Mitra [162] and Experiment 1 only in that the distance of each item from the viewpoint was randomly assigned within a fixed depth range. The reason for this was to test the frame co-registration hypothesis on the most general possible combination of standing upright and visually searching for patterns of interest in the environment. The change from the standard 2-D visual search displays used most often in experimental work to the 3-D versions used in this thesis could be, however, theoretically non-neutral. Firstly, searching a 3-D display increases the load and complexity of accurate visual fixation by requiring more vergence and accommodation changes than a planar display. This difference may have added to the effective load of the search component, which could have impacted resource distribution between the postural and cognitive task components. Secondly, the 3-D search display made visual information such as motion parallax (of particular interest in the control of ML sway) and retinal velocity gradient (useful in the control of AP sway) more prominent. Thus, the addition of depth in the search display may have added to cognitive task-load while simultaneously offering informational means of reducing postural task-load. For both these reasons, the question of the sensitivity of the thesis dual-task paradigm to the presence of depth variation in the search display is an important one. This final experiment in the series was conducted to address this issue. Participants were asked to focus on performing quick and accurate search for a visual target set in split frames, as in Experiments 4 to 5, but in which the displays were with or without depth variation. In view of the length of the experimental session and participant comfort, participants performed the search task in the more natural open stance condition only.

6.4.1 Method

Method was as described for Experiment 5, but with the following differences.

6.4.1.1 Participants

Twenty-six undergraduate students from the University of Warwick participated in the study, receiving course credit for their participation. They ranged from 18 to 22 years in age, 1.59 to 1.86 m in height, and 53 to 75 kg in weight. All reported normal or corrected-to-normal vision, and none had any history of neurological or balance disorders. All participants were naïve to the purpose of the experiment, and were debriefed in detail only after data collection was completed. None of the participants had participated in a posture control experiment before, nor previously undertaken a visual search task in the laboratory. Two participants' data were eliminated from all analyses due to measurement errors during sway data collection.

6.4.1.2 Stimuli, and experimental procedures

The visual search display was presented either as a planar surface at the convergence distance as in Experiment 1, or with the items randomly staggered in depth exactly as in Experiments 2 to 5. The search task was always performed in an open stance condition.

6.4.2 Results

6.4.2.1 Visual search

Analysis of variance (ANOVA) was conducted on percent accuracy and RT with repeated measures on target (present, absent), frame (coincident, non-coincident), search-load (low, high) and depth (2-D, 3-D) within-participants factors.

Accuracy. ANOVA showed significant main effects of search-load ($F_{(1,\ 23)}$ = 23.373, $p < .001$, $\eta^2_p = .504$; accuracy was greater in the low search-load condition), and target ($F_{(1,\ 23)}$ = 31.317, $p < .001$, $\eta^2_p = .577$; accuracy was greater in the target-absent condition). Accuracy on target-present trials dropped significantly as search-load increased ($F_{(1,\ 23)}$ = 26.788, $p < .001$, $\eta^2_p = .538$), but there were no significant differences in the corresponding target-absent conditions. The 4-way interaction was significant (see Figure 6-2), $F_{(1,\ 23)}$ = 5.264, $p < .05$, $\eta^2_p = .186$; for search in 2-D displays under low search-load, accuracy was significantly lower on present trials than absent trials in the non-coincident frames condition, ($F_{(1,\ 23)}$ = 4.600, $p < .05$), but there were no significant differences in the corresponding coincident frames conditions. For 3-D displays under low search-load, accuracy was significantly greater on absent trials than present trials in coincident frames ($F_{(1,\ 23)}$ = 6.457, $p < .05$), but there were no significant differences in the corresponding non-coincident frames conditions. All other (Bonferroni-corrected) pairwise comparisons were significant.

Response Time. On the RT measure, there were significant main effects of search-load ($F_{(1,\ 23)}$ = 420.334, p < .001, η^2_p = .948; RT was faster in the low search-load condition), and target ($F_{(1,\ 23)}$ = 130.146, p < .001, η^2_p = .850; RT was faster in the target-present condition). The search-load × target interaction was significant, $F_{(1,\ 23)}$ = 143.718, p < .001, η^2_p = .862; RT rose more sharply in the target-absent than the target-present condition as search-load increased, $t_{(23)}$ = 11.988, p < .001. The

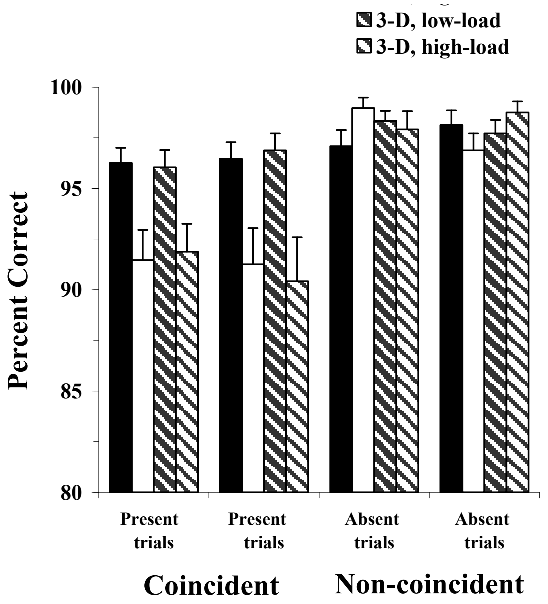

Figure 6-2 Percent accuracy for display and search-load conditions on present and absent trials as a function of reference frame in Experiment 6. Error bars show standard errors of the means.

average search slope was 0.032 s/item on target-present trials, and 0.074 s/item on target-absent trials. Overall, RT was significantly greater for 3-D than 2-D displays ($F_{(1, 23)} = 11.073, p < .01, \eta^2_p = .325$). Depth interacted significantly with search-load $F_{(1, 23)} = 44.408, p < .05$; under high search-load, RT was greater for 3-D than 2-D displays ($F_{(1, 23)} = 8.326, p < .01, \eta^2_p = .266$), but there were no significant differences in the corresponding low-search-load conditions (see Figure 6-3).

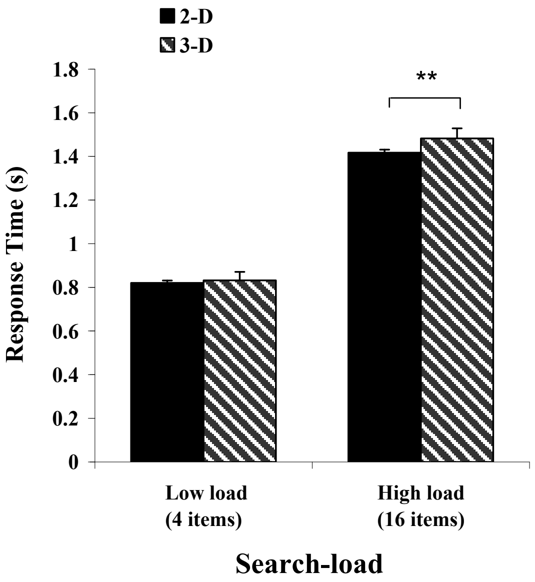

Figure 6-3 Response time for 2-D and 3-D displays as a function of search-load in Experiment 6. Error bars show standard errors of the means. Asterisks denote effect of interest statistically significant at the $p < .01$ level.

6.4.2.2 Postural sway

Repeated measures ANOVA was conducted on the shorter time-scale (STS) and longer time-scale (LTS) measures, separately for ML and AP sway, with frame (coincident, non-coincident), search-load (low, high) and depth (2-D, 3-D) as within-participants factors.

Head Sway. On the STS-ML measure of the head's ML sway, the frame × load interaction was significant, $F_{(1,\ 23)} = 5.771$, $p < .05$, $\eta^2_p = .201$; STS-ML sway rose significantly in the coincident frames condition as search-load increased ($F_{(1,\ 23)} = 5.765$, $p < .05$, $\eta^2_p = .200$), but there were no significant differences in the corresponding non-coincident frames conditions (see Figure 6-4, top panel). Also, STS-ML sway was significantly greater in coincident frames than non-coincident frames under high search-load conditions, $F_{(1,\ 23)} = 5.992$, $p < .05$, $\eta^2_p = .207$). There were no significant main effects and no significant interactions for the short time-scale measure of the head's AP sway. Turning to the longer time-scale measures, LTS-ML sway rose significantly in the coincident frames condition as search-load increased ($F_{(1,\ 23)} = 5.621$, $p < .05$, $\eta^2_p = .196$), but there were no significant differences in the corresponding non-coincident frames conditions (see Figure 6-4, bottom panel). There were no significant main effects and no significant interactions for the head's LTS-AP measure.

Hip Sway. There were no significant effects on any of the measures.

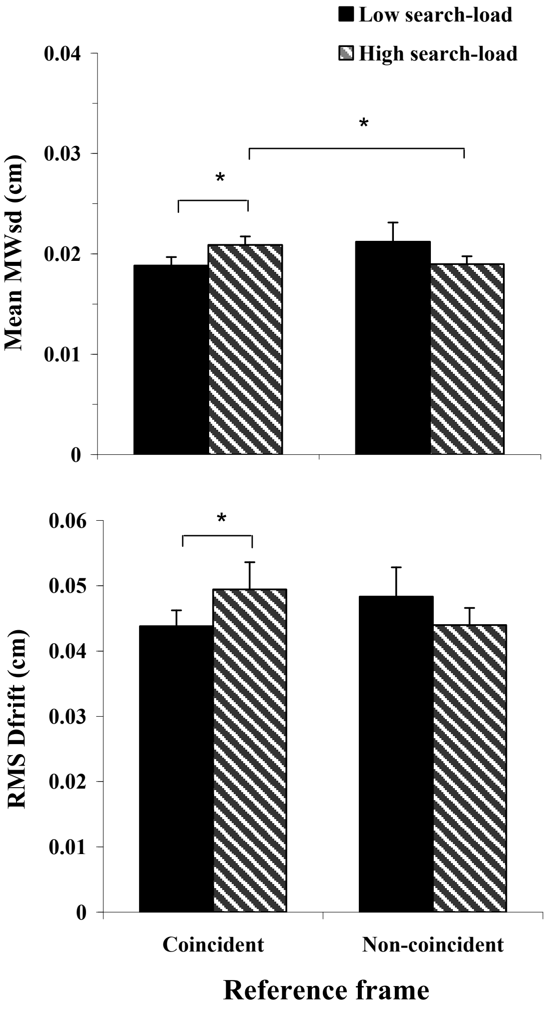

Figure 6-4 STS and LTS of the head's ML sway for low and high search-load as a function of reference frame in Experiment 6. Top panel shows STS, and bottom panel shows LTS. Error bars show standard errors of the means. Asterisks denote effects of interest statistically significant at the $p < .05$ level.

6.4.3 Discussion

Work on visual search in depth [158; 167; 169] suggests, on balance, that conjunction search with stereo depth as an attribute is no more inefficient than search for a target defined by other features or spatial relations [167]; see also [195]. However, for the task conditions of the present study, adding depth to the search displays significantly affected search performance—as search-load increased, RT rose more sharply for 3-D displays than for 2-D displays. Since the search items in the 3-D displays appeared randomly staggered in depth, the task of repeated visual fixations during search may have been considerably more demanding than for the 2-D display (or even one with items placed on multiple surfaces at different depths). Accuracy remained high, however, with the lowest accuracy score being 91.3%, in target-present, high search-load condition.

The presence or absence of depth variation in the search displays had no effect on postural sway. There was no evidence therefore, the added visual support for posture control provided in the 3-D displays was taken up by participants, at least when performing search while standing in open stance, and in the absence of explicit instruction to control sway. Given that, as in Experiments 2 and 3, half the search items maintained their positions in the world-frame and half moved with the swaying viewpoint, participants' head sway would have generated some relative (apparent) motion between the items in the two frames in both the 2-D and 3-D conditions. Though this relative motion would have been greater in the 3-D condition, this difference may not have been important in terms of using parallax for controlling ML sway.

The significant interaction between frame and search-load found for the head's ML sway at both time-scales suggests that when the search target appeared in the world-frame (coincident frames condition), increased search-load reduced participants' ability to control their ML sway. In this frame condition, the search display may have been segmented early in each trial by colour (or motion) grouping of the green distractors presented in the non-coincident task-frame. If resources for both visual search and posture control then remained focused primarily on the world-frame alone, the ability to extract parallax from the relative optical motion of the green and blue item-groups may have been compromised. This would have particularly affected control of ML sway, which is sensitive to the presence of parallax information. Though the mean difference was in the opposite direction when the target appeared in the task-frame (non-coincident condition), the lack of significance would suggest that when the search task was anchored away from the postural world-frame, extraction of parallax did not differ across the load manipulation. With respect to the main purpose of the present experiment, however, the key point to note is that the presence or absence of depth variation in the search displays did not make any measurable impact on any of the measures of postural sway. A reasonable overall conclusion from these results seems to be that the use of the 3-D version of the visual search task simply added to its level of difficulty or resource requirements, but did not significantly alter the usefulness of the search display for posture control. Since the present experiment did not also test under the more demanding closed stance or explicit sway minimization conditions, this conclusion cannot be wholly generalized to all possible testing conditions. However, the conditions not included in this experiment would impose even higher levels of overall load on participants, making it less likely to elicit subtle performance variations that could be observed in this experiment.

Chapter 7

Postural Costs of Performing Cognitive Tasks in Non-Coincident Reference Frames: Mental Rotation

7.1 Introduction

The visual search experiments examined the co-registration hypothesis in context of items located in external space. However, as humans, many of our cognitive operations require mentally arranging, remembering and manipulating spatial relations and object properties. There is evidence to suggest that these operations have a sensorimotor basis [277; 278], and several studies have demonstrated the body as having an important modifying role in imagined spatial transformations such as mental rotation tasks ([12; 189-192; 230]; see [225], for a commentary). A methodological consideration also exists in that the load manipulation in the visual search experiments was confounded with the presence of additional perceptual stimuli in the field in the high-load cognitive task condition. Using a cognitive task such as mental rotation, on the other hand, allows the examination of the frame co-registration cost hypothesis for a task in which cognitive load is manipulated while keeping perceptual load constant (in the sense of the number of items in the field).

In the present experiment, participants were required to perform quick and accurate mental rotation judgments under conditions in which the identity and parity/non-parity objects could be jointly presented in either a world-frame (coincident condition) or in a head-anchored task-frame (non-coincident condition). A frame co-registration cost hypothesis would predict that the non-coincident frames condition should generate a greater performance cost to posture control than performing mental rotation in the coincident frames condition, over and above costs of postural or cognitive task-load.

7.1 Method

General method was given in Chapter 3. In the coincident frames condition, the mental rotation objects (described below) appeared in a world-frame (i.e., the object pair kept their position and orientation in the world-frame). In the non-coincident frames condition, the object pair appeared and maintained position-orientation with respect to the observer's head.

7.2.1 Participants

Twenty participants (undergraduates and postgraduates) from the University of Warwick participated in the study, receiving payment for their participation. They ranged from 18 to 26 years in age, 1.56 to 1.87 m in height, and 52 to 73 kg in weight. All reported normal or corrected-to-normal vision, and none had any history of neurological or balance disorders. All participants were naïve to the purpose of the experiment, and were debriefed in detail only after data collection was completed. Several participants had taken part in a posture control experiment, but none had previously performed an experiment involving mental rotation.

7.3 Results

7.3.1 Mental rotation

Analysis of variance (ANOVA) was conducted on percent accuracy and response time with repeated measures on judgment condition (parity, non-parity), frame (coincident, non-coincident), rotation (50^o, 100^o, 150^o) and stance (open, closed) within-participants factors.

Accuracy. On the percent accuracy measure, ANOVA showed a significant main effect of judgment, $F_{(1,\ 18)} = 32.683$, $p < .001$, $\eta^2_p = .645$; accuracy was greater for parity objects. The main effect of rotation was significant, $F_{(1,\ 18)} = 62.210$, $p < .001$, $\eta^2_p = .766$; accuracy for parity/non-parity judgments increased as the displacement angle size increased—50^o vs. 100^o ($t_{(18)} = 5.161$, $p < .001$), 50^o vs. 150^o ($t_{(18)} = 9.673$, $p < .001$) and 100^o vs. 150^o rotations ($t_{(18)} = 7.217$, $p < .001$). There were no significant effects involving the reference frame factor.

Response Time. The main effect of judgment was significant, $F_{(1, 18)} = 55.843$, $p < .001$, $\eta^2_p = .756$; RT was faster for parity judgments. The main effect of rotation was significant, $F_{(1, 18)} = 41.938$, $p < .001$, $\eta^2_p = .700$; parity/non-parity judgments were significantly greater across rotation conditions—50° vs. 100° ($t_{(18)} = 5.172$, $p < .001$), 50° vs. 150° ($t_{(18)} = 7.367$, $p < .001$) and 100° vs. 150° rotations ($t_{(18)} = 5.516$, $p < .001$). There were no significant effects involving the reference frame factor.

7.3.2 Postural sway

Repeated measures ANOVA was conducted on the shorter time-scale (STS) and longer time-scale (LTS) measures, separately for ML and AP sway, with frame (coincident, non-coincident), rotation size (50°, 100°, 150°) and stance (open, closed) as within-participants factors.

Considering the head segment first, on the STS measure and for ML sway (see Figure 7-1, top-left panel), there was a significant main effect of stance, $F_{(1, 18)} = 214.108$, $p < .001$, $\eta^2_p = .922$; STS-ML sway was greater in the closed stance. The main effect of frame was marginally significant, $F_{(1, 18)} = 4.266$, $p = 0.54$, $\eta^2_p = .192$; STS-ML sway was marginally greater in the non-coincident ($M = .027$, $SE = .001$) than the coincident frames condition ($M = .025$, $SE = .001$). The stance × rotation interaction was significant, $F_{(1, 18)} = 3.767$, $p < 0.5$, $\eta^2_p = .173$; STS-ML sway rose significantly in open stance as rotation angle increased from 50° to 100° ($F_{(2, 36)} =$

4.172, $p < .05$, $\eta^2_p = .329$), but there were no significant differences in the corresponding closed stance conditions (see Figure 7-2, top panel). On the STS-AP measure (see Figure 7-1, top-right panel), there was a significant main effect of stance, $F_{(1,\,18)} = 20.477, p < .001$, $\eta^2_p = .532$; STS-AP sway was greater in the closed stance. The rotation × stance × frame interaction (see Figure 7-3) was significant, $F_{(2,\,36)} = 3.739$, $p < .05$, $\eta^2_p = .172$; for 150° rotations, STS-AP sway was greater under closed than open stance in the non-coincident frames condition ($F_{(1,\,18)} = 5.027$, $p < .05$), but there were no significant differences in the corresponding coincident frames conditions.

Turning to the LTS measure, on ML sway (see Figure 7-1, bottom-left panel), the main effect of stance was significant, $F_{(1,\,18)} = 192.969, p < .001$, $\eta^2_p = .915$; LTS-ML sway was greater in the closed stance. Also, there was a significant main effect of frame, $F_{(1,\,18)} = 5.388, p < 0.5$, $\eta^2_p = .230$; LTS-ML sway was greater in non-coincident ($M = .072$, $SE = .004$) than coincident frames ($M = .065$, $SE = .003$). The stance × rotation interaction was significant, $F_{(1,\,18)} = 4.401, p < 0.5$, $\eta^2_p = .196$; LTS-ML sway rose significantly in open stance as rotation angle increased from 50° to 100° ($F_{(2,\,36)} = 4.782, p < .05$, $\eta^2_p = .360$), but there were no significant differences in the corresponding closed stance condition (see Figure 7-2, bottom panel). On the LTS-AP measure (see Figure 7-1, bottom-right panel), the main effect of stance was significant, $F_{(1,\,18)} = 12.051, p < .01$, $\eta^2_p = .401$; LTS-AP sway was greater in the closed stance. The main effect of frame was significant, $F_{(1, 18)} = 7.1298, p < .05, \eta^2_p = .284$; LTS-AP sway was greater in the non-coincident ($M = .096$, $SE = .003$) than the coincident frames conditions ($M = .091$, $SE = .003$).

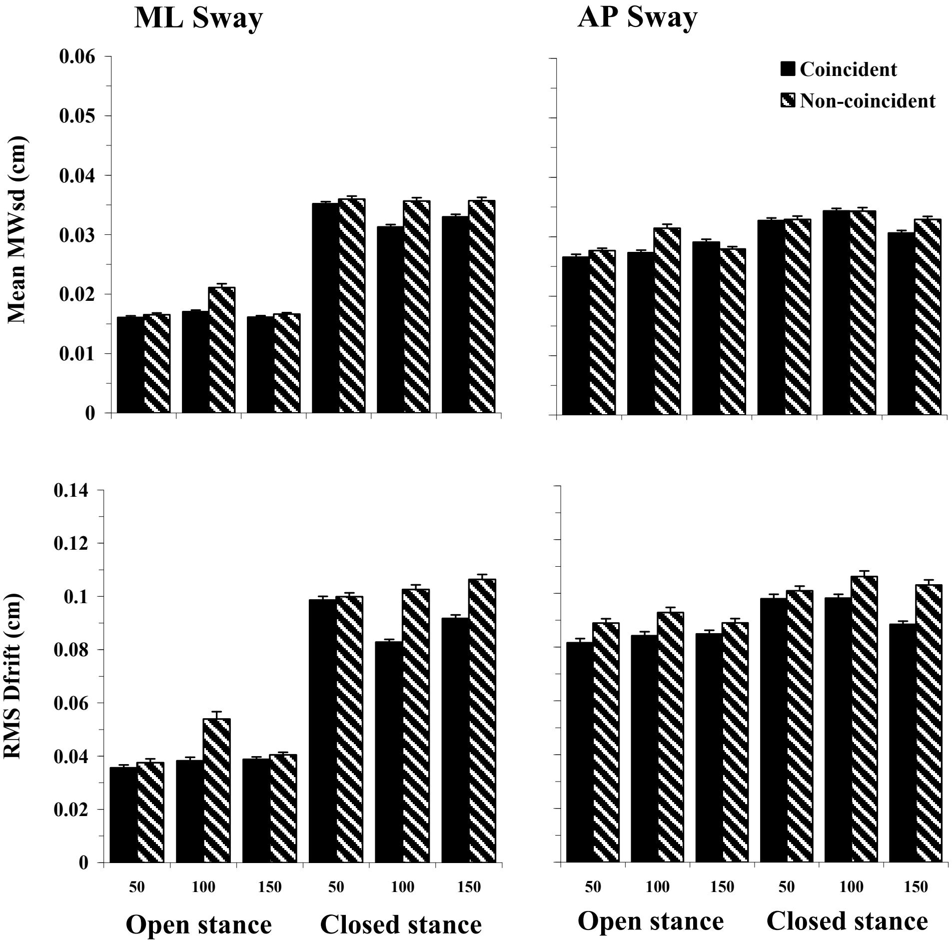

Figure 7-1 ML (left panels) and AP (right panels) on the head's sway for coincident and non-coincident frames under rotation difficulty conditions as a function of stance in Experiment 7. Top panels show STS and bottom panels show LTS. Error bars indicate standard error of the means.

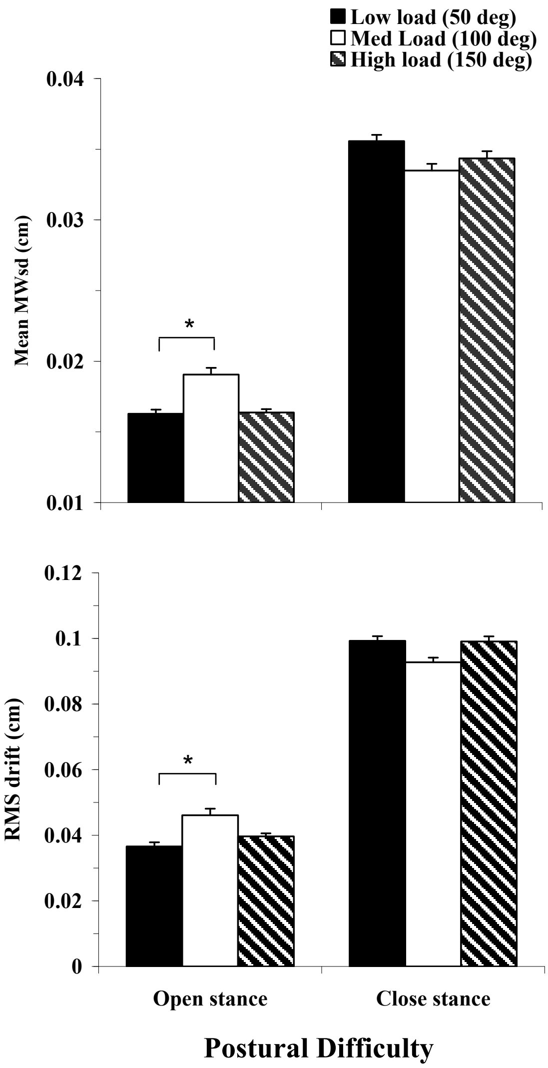

Figure 7-2 ML of the head's sway for rotation size as a function of postural difficulty for Experiment 7. Top panel shows STS and bottom panel shows LTS. Error bars show standard error of the means. Asterisks denote effects of interest statistically significant at the $p < .05$ level.

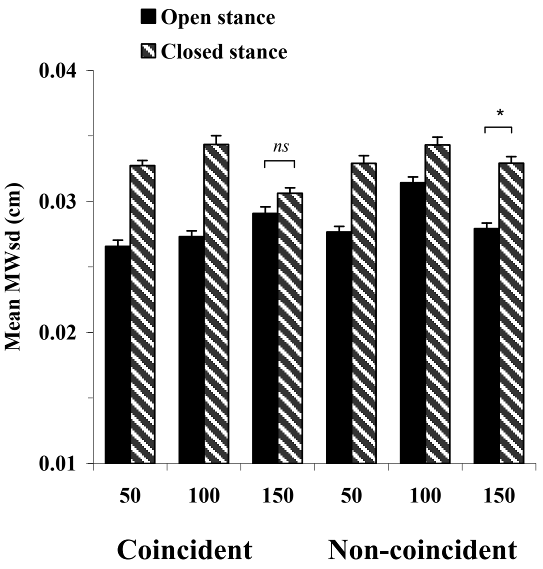

Figure 7-3 STS-AP of the head's sway for open and closed stance under rotation difficulty conditions as a function of reference frame for Experiment 7. Error bars show standard error of the means. Asterisk denotes effect of interest statistically significant at the $p < .05$ level.

Considering the hip segment, on the STS measure and for ML sway (see Figure 7-4, top-left panel), ANOVA showed a significant main effect of stance, $F_{(1,\ 18)} = 67.039$, $p < .001$, $\eta^2_p = .788$; STS-ML sway was greater in the closed stance. On the STS-AP measure (see Figure 7-4, top-right panel), there was a significant main effect of stance, $F_{(1,\ 18)} = 7.998$, $p < .05$, $\eta^2_p = .308$; STS-AP sway was greater in the closed stance. The main effect of frame was significant, $F_{(1,\ 18)} = 5.139$, $p < .05$, $\eta^2_p = .222$; STS-AP sway was greater in the non-coincident ($M = .023$, $SE = .001$) than the coincident frames condition ($M = .021$, $SE = .001$).

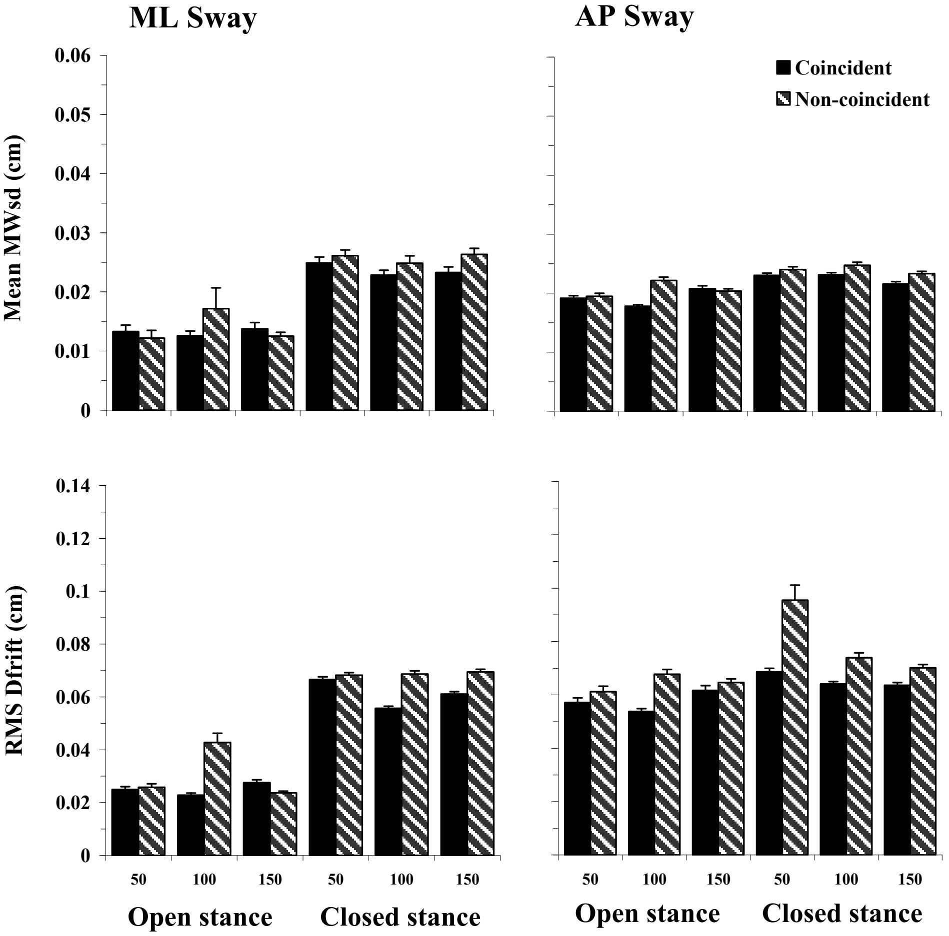

Figure 7-4 ML (left panels) and AP (right panels) on the hip's sway for coincident and non-coincident frames under rotation difficulty conditions as a function of stance in Experiment 7. Top panels show STS and bottom panels show LTS. Error bars indicate standard error of the means.

Turning to the LTS measure, considering LTS-ML sway first (see Figure 7-4, bottom-left panel), ANOVA showed a significant main effect of stance, $F_{(1,\ 18)}$ = 79.217, p < .001, η^2_p = .815; LTS-ML sway was greater in the closed stance. The main effect of frame approached significance, $F_{(1,\ 18)}$ = 3.970, p = .062, η^2_p = .181;

LTS-ML sway tended to be greater in the non-coincident frames condition. On the LTS-AP measure (see Figure 7-4, bottom-right panel), the main effect of frame was significant, $F_{(1,\ 18)} = 5.429$, $p < .05$, $\eta_p^2 = .232$; LTS-AP sway was greater in the non-coincident ($M = .071$, $SE = .003$) than the coincident frames condition ($M = .064$, $SE = .003$).

7.4 Discussion

On the characteristics of the mental rotation task, participants' RTs were significantly greater, and accuracy significantly lower, across rotation conditions, confirming that the rotation size manipulation effected a significant change in cognitive-load. Participants' responses on average ranged from 2 s for 50^o rotations to 3.4 s for the more difficult 150^o rotations, typical of times found for matching standard Shepard-Melzer objects (about 1 sec at 0 degree of rotation for all participants, increasing to values ranging from 4 to 6 seconds at 180 degrees of rotation, [232]). The strong correlation ($R^2 = 96.6$, $p = .058$, non-transformed data) for RT and angle of rotation found here is consistent with studies in which participants are believed to have mentally rotated stimuli using an exocentric viewpoint [57; 232; 288; 297; 298].

On the postural side, participants swayed more in both ML and AP directions on 7 of the postural measures when they stood in the more difficult, closed stance.

Though the cognitive performance measures indicated that the mental rotation task was attentionally demanding, rotational difficulty had only limited effect on postural sway. On both time-scales of the head's ML sway, increasing rotational difficulty from 50 to 100 degrees lead to significantly increased sway in open stance and, as can been seen from Figure 7-2, produced a trend towards reduced sway in closed stance. For both measures, increasing rotational difficulty still further, from 100 to 150 degrees, produced a trend reversal of this pattern, with a tendency towards reduced sway in open stance and towards increased sway in closed stance. A straightforward explanation for these results is that as the mental rotation began to increase in difficulty (i.e., from 50^o to 100^o rotations) people allowed themselves to sway more in the secure open stance in order to maintain performance on the cognitive task. As the cognitive task became progressively more difficult (150^o rotations) however, available resources were progressively consumed, leading to greater sway in the less secure closed stance.

Overall experimental conditions the effect of frame co-registration was robust, with 4 of the postural measures (and two further measures, marginally) indicating increased sway when the dual-task had to be performed in non-coincident reference frames. The pattern of interaction found on the STS-AP measure of the head sway involving frame, rotation and stance factors showed that, though sway levels could be maintained across postural difficulty conditions, participants could not contain the added demands of frame non-coincidence under combined high-load postural and cognitive conditions. These results confirm the importance of the frame co-registration cost hypothesis for concurrent activities involving postural control and imagined spatial transformations for a cognitive task.

Chapter 8

General Discussion and Broader Implications

The series of experiments presented in this thesis were designed to show that, in the context of posture-cognition dual-tasking, placing a cognitive task component in a reference frame other than the postural task's world-frame incurs measurable postural costs. The frame manipulation (Experiments 2-7) essentially involved placing a visual search or mental rotation task in a natural reference frame that was either in coincidence with the world-frame (i.e., the postural component's natural frame), or in coincidence with the standing participant's swaying head (i.e., non-coincident with posture control's natural frame). Since spontaneous sway in the upright stance has high-dimensional dynamics, in the non-coincident frames condition, participants could not dynamically map the world and task frames to each other. However, they did have access to vestibular and somatosensory information about the task-frame's instantaneous motion relative to the world-frame. The results to the visual search experiments (see summary Table 8-1, page, 171) showed that non-coincidence of the task components' natural reference frames led to performance decrements in the cognitive (Experiment 2) as well as the postural task (Experiments 2–5). This pattern persisted across instruction variations that prioritized the cognitive task (Experiments 2 and 4) or specified deliberate sway minimization (Experiments 3 and 5). The pattern also persisted when the visual search task was split between coincident and non-coincident frames and both frame conditions were rendered identical in terms of visual information relevant to posture control (Experiments 4 and 5). Thus, the posture control deficits observed in the non-coincident frames condition were not an artefact of differences in available visual information for posture control. Also, in Experiments 3-6, differences in visual search performance across the two frame conditions were eliminated, so differences in posture control could not be due to differential search task difficulty in the two frame conditions. Finally, the results to Experiment 7 showed that there can be significant postural costs for concurrent activities involving postural control and internally generated and maintained representations for a cognitive task. Since, in several cases, the undesirable effects of frame non-coincidence were found in the most demanding combination of closed stance and high cognitive load, it is concluded that the act of keeping two non-coincident frames in register itself incurred costs over and above those of the task components themselves.

The experiments were not equipped to test whether co-registration costs arise from having to perform coordinate transformations to align the reference frames of the two components, or whether the co-registration process requires continuous updating of the state of one frame to the other. The observed performance costs nonetheless a striking observation about embodied cognition, because the dual-task of standing upright while engaged in cognitive tasks is endemic to everyday life, often involving non-coincidence of postural and cognitive frames (for example, standing and looking at a moving person or object, or reading a piece of paper held in the hands). Since the central nervous system evidently has a wide choice of reference frames available for use (see, e.g., [27; 46]), the inability of participants to effortlessly solve the frame non-coincidence problem in such a common task combination suggests that concurrent tasks with non-coincident reference frames can effectively partition a common workspace into multiple non-compatible task-spaces. If so, any given event such as a body or stimulus movement can have entirely different consequences for performance in different task-spaces. This can make it difficult, if not impossible, to operate simultaneously in the interest of both task components. In the case of visually searching while standing upright, this point can be well appreciated by examining how the eye-head system must be used during dual-task performance.

On the posture control side, visual and vestibular systems used to stabilize sway are embedded in the head, and being a heavy body segment with a significant amount of moment about the pivot point at the ankle, its motion is also a significant contributor to the proprioceptive feedback from body sway.[9] Also, sway during upright stance

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[9] For tasks critically dependent on head stabilization and involving small body movements, head movement can be greater than trunk movement [202; 203]. More generally, for paradigm-types involving small amplitude movements, healthy young and middle-aged adults show a preference for an ankle strategy [66; 86].

is thought to have both a performatory (i.e., corrective) as well as an exploratory element [214; 221]. Riccio [214] has proposed, for example, that low-frequency modulation of high-frequency sway variability can serve as a source of information about ongoing postural dynamics (see also, [31; 145], for further examples on information generating functions of movement variability). In this sense, postural movements of the eye-head system can be the result of a corrective action, an exploratory modulation, or uncorrected drift. In all cases, however, eye-head movements generate vestibular, proprioceptive (and, depending on task conditions, visual) signals that have specific implications for posture control in the world-frame.

On the visual search side, the task itself involves multiple, high-precision eye movements that are easier to execute if the relative motion between the head and the search display can be minimized [245]. Equally, searching can engage both overt and covert attention in a way that may be incompatible with extracting any posture-relevant visual information that may be present in the visual field (as, perhaps, in Experiments 3 to 6). Also, if the search task's display-anchored reference frame is used to code item locations, the code needs to be invariant over eye and head movements. Thus, any eye-head movements associated with performatory or exploratory postural activities can add to the search task's difficulty by complicating location coding. Perhaps most crucially, the same eye-head movement can mean different and incompatible things in the world and search task-frames. In the world-frame, the movement may be an excursion that needs to be corrected, or a beneficial exploration that generates valuable information for posture control. In the search task-frame, the very same eye-head movement may be either an unwanted transform over which location codes need to be kept invariant, or a helpful act of orienting to an item of interest. Furthermore, the level of incompatibility between these different meanings of the same eye-head movement depends strongly on both the choice of task-frame as well as the relative motion of the world- and task-frames.

Such sources of dual-task interference have long been of interest to action-oriented theorists, who view dual-task capacity limitations as a by-product of functional selection problems [7; 175] that centre, in particular, on the spatial arrangement of task components [177]. Neisser [175] suggested, for example, that capacity limitations can arise simply because two actions are physically incompatible (see also, [177] on 'blocking') or because stimuli relevant to the two tasks may mask each other, or because there is a "genuine informational impediment to the parallel development of independent but similar schemata" (p. 103) due to difficulties in applying new perceptual information to the correct schema (see also, [8; 9], on the problem of crosstalk). Direct clashes between eye-head movements required by posture control and visual search, as well as the difficulties in using the information generated by eye-head movements to guide either task may well have contributed to the co-registration costs observed in the visual search experiments. Similarly, when mentally rotating an object, clashes may occur in the holding and use of sensorimotor information for the orientating frame and in the concurrent retention and allocation of information used for operations in the cognitive task frame.

While an action-oriented framework would seem natural choice for organizing the reference frame related issues that arise in posture-cognition dual-tasks, concepts such as selection-for-action [8] would need to be significantly updated before they could be fruitfully applied to dual-tasks involving complex coordination components. This is because these theories were originally devised around dual-task paradigms with relatively impoverished action requirements (for example, single-digit button-presses), and therefore over-identified 'action' with 'output' (when 'action' is just as significant a component of perceptual 'input' when we consider coordination tasks). Also, these theories often used simplistic conceptions of sensory-motor mapping that grossly underestimated the considerable complexities of using perceptual information to effectively guide large-scale, multi-segment body coordination (see, e.g., [164]). Similarly, structural accounts of dual-task interference based, for example, on the simultaneous use of the visuospatial sketchpad [116; 151] would need to be extended with details of exactly how dual-tasks with non-coincident reference frames must be managed in working memory. Given that the importance of studying cognition in its naturally embodied state continues to increase, such theoretic efforts would appear to be well worth undertaking.

The notion, from action-orientation accounts, that attentional limitations arise where stimuli have to be kept apart, not where they have to be combined [177], is particularly resonant with the requirement of keeping tasks activated and maintained with respect to more than one task-linked reference frame at a time. One way of tackling barriers to dual-tasking such as the ones identified above would be to evolve a strategy for alternating between perceiving and acting with respect to two coordinations, and modulating the proportion of time allotted to each. The success of such a strategy would depend heavily, of course, on each task's tolerance to time delays due to turn taking. In this respect, cognition-coordination dual-tasking comes with the further constraint that posture control has a natural time-scale dictated by the inertial properties of the body—regardless of the cognitive component's requirements, the time-scale of corrective adjustments to body posture cannot be stretched beyond a physically dictated limit without risking stance destabilization. As earlier discussed, evidence suggests that this limit for unperturbed upright stance could be somewhere in the region of 1 s [53; 219].[10]

While the impact of shared resources on temporal processing for postural control has not gone unappreciated [213], the profound implication of gravitationally governed time limits in posture-cognition dual-tasks is that any cognitive task that conflicts with postural coordination in the above manner must at least periodically yield the use of common control and articulatory dimensions. The implication of this strategy is straightforward but profound—any cognitive task that conflicts with postural coordinations in the above manner must at least periodically yield the use of common control and articulatory dimensions at a time-scale dictated by gravity. The

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[10] The time-scale for the visual search task was approximately 0.8 s and 1.5 s per trial, respectively, in low- and high-load conditions.

impact of such a constraint on the evolution of cognitive skills generally, and the cognitive architecture required to support them, merits detailed consideration in due course. More immediately, it suggests a more precise interpretation of ‘resource competition’ or ‘resource sharing’ in posture-cognition dual-task performance—the effects that are attributed to competition for limited resources between posture control and cognitive tasks such as visual search—may well be effects of time-sharing between underlying coordinations. Increasing the cognitive task’s time allocation (for example, by increasing the number of search items) may slow down the time-scale of postural corrections, leading to greater sway dispersal, as observed for effects of frame non-coincidence on the longer time-scale measure in Experiment 5. Equally, shortening the time-scale of postural corrections (for example, by introducing a less stable closed stance or requiring deliberate sway reduction) can squeeze the size of the time intervals available to the cognitive task. In the case of visual search, this could lead to a flattening of search slopes (at some expense to accuracy), an apparently anomalous performance enhancement effect was actually observed in Experiment 1 and in other work with the present paradigm [162].

If time is in fact the ‘resource’ that is shared between a postural and a suprapostural cognitive task, then the coexistence of facilitation and competition effects envisaged in Mitra’s adaptive resource-sharing theory [162; 163] can be examined in a clearer light. The control of upright stance has gravitationally governed tolerance limits in terms of allowable spatial dispersal and therefore time-scale of corrective action.

Well within these limits, the time requirements of another task can be absorbed and common control and articulatory dimensions recruited to facilitate the task. As the tolerance limits are approached, however, the effects of time-sharing become observable. Depending on the required time-scale of responding, time-sharing with posture control can both slow down as well as speed up task performance.

A variety of everyday tasks such as reading, manipulating, tracking or intercepting moving objects, and even mentally imaging events other than the current physical task context, can all present complex frame co-registration requirements that far exceed the challenges presented by the subtle manipulations in the present experiments. Furthermore, healthy, young adults, the population tested in this study, are in fact the least likely to be affected by such frame co-registration challenges. Among the elderly, for example, there is strong evidence of particular postural vulnerability to the demands of concurrent cognitive task performance [40; 151; 209; 212; 235]. A suggested cause is a failure to adequately and flexibly stabilize the vestibular apparatus and eye-head system in space for purpose of processing sensory feedback [71; 289]. While a head-in space strategy relies mainly on a geocentric frame of reference, both egocentric and exocentric frames are thought to contribute toward the control of head stabilization [71], and which conceivably could be brought into conflict in dual-task situations such as those studied here. In light of the present results with young adults, therefore, it would be worth investigating the extent to which the elderly are particularly vulnerable in task situations with frame co-registration requirements.

It is perhaps be at the other end of the lifespan, however, where the coexistence of cognitive and postural task-frames, and the effects of their dynamic relationship, assume their greatest importance. As discussed in the introduction, a major impetus to the study of embodied cognition came from research on the profound ways in which sensorimotor development underpins cognitive skill acquisition. The attainment of stable stance and gait are present substantial challenges for the maturing posture control system. If the costs to posture control of maintaining stable cognitive task-spaces are clearly discernible in healthy young adults, as the present research has shown, the costs to the immature posture control system of not only maintaining balance, but also supporting the often erratic sensorimotor activity accompanying emerging cognitive skills, must be substantial. The extent to which contention scheduling between postural and cognitive functions, especially between their respective task-spaces or reference-frames, governs the co-emergence of posture control and cognitive competence must therefore be well worth studying closely in children.

In this respect, one issue of significant interest could be the manner in which impaired or inefficient contention scheduling between concurrent postural and cognitive task-spaces may affect embodied cognition in early life. It is worth noting, for example, the mounting evidence that in some developmental disorders, such as dyslexia [179-181] and the autistic spectrum [174], the cognitive impairments that define the conditions are often accompanied by systematic balance and coordination difficulties. The causal links between the postural and cognitive impairments in these disorders are currently a topic of considerable debate, but there appear to be some remarkable similarities between the proposed reasons for motor impairments in these otherwise dissimilar cognitive disorders. In cognitive terms, one proposal is that both dyslexia and autism involve difficulties in shifting attention from one activity to another (for reviews, see [109], on dyslexia, and [174], on autism and Asperger's disorder). Another possibly related proposal is that both conditions involve deficits in temporal information processing [34; 81; 285]. In anatomical terms, both conditions are said to have a component of cerebellar dysfunction [6; 58; 181], which may be a locus of both the temporal processing as well as attention-shifting impairments, although dysfunction of the posterior parietal cortex in dyslexia [109] and the basal ganglia in autism [174] may also be important contributors.

A possible link between these two cognitive impairments and the balance and gait difficulties associated with these disorders may lie in inefficient time-sharing between operations in postural and cognitive task-spaces. As already discussed, concurrently performing postural and cognitive tasks, especially in non-coincident reference frames, may often require alternating between acting with respect to one frame or the other. Since the two task components draw on common attentional resources, any difficulty in switching attention between tasks (i.e., alternately allocating shared resources to either component) is likely to be particularly disruptive to posture-cognition dual-tasking. If there are temporal information-processing difficulties as well, these can only compound the problem given that posture control is subject to a gravitationally dictated time-scale for corrective actions, and that the time-course of postural corrections and cognitive operations must therefore be finely coordinated for both tasks to proceed without significant disruption. As shown in the present work, both attention-switching and temporal processing impairments are likely to have a greater impact on posture control as the cognitive task's reference frame becomes less closely tied to the world-frame. This, however, is exactly the expected pattern in early life as children progress from attending to static objects and patterns to interacting with dynamic ones held in their own hands or moving independently in the world. It would seem, therefore, that a detailed investigation of the sensitivity of coordination deficits in developmental disorders such as dyslexia and autism to spatio-temporal relationships between postural and cognitive task-spaces may well provide important theoretical insights into the cognitive and coordination deficits associated with these disorders.

Table 8-1 Summary of experimental results to the thesis

Notes.

(1) Key to postural measures

Balance control measures: acronyms, descriptions and measures	
SDmw	Moving window standard deviation— mean moving SD of the COM time series, mm/s
RMSmw	Root mean square of the mean moving SD of the COM time series, mm/s

(2) Reported effects of postural and cognitive difficulty levels were nil, unless otherwise indicated. ML = medial-lateral sway and AP = anterior-posterior sway directions.
† Indicates marginally significant effect (*p* > .05 < .06).

Dual-task	Population	Sway Instr.	Effect of cognitive task	Effect of postural task
Unperturbed wide- and narrow-base standing				
EXP 1: Conjunction visual search (2 levels) in 2-D. All search items in world frame.	Young adults (*n* = 20)	Cognitive task-focus vs. Dual-task focus	**Posture sway increased** HEAD SEGMENT: • STS-ML, STS-AP, LTS-ML, LTS-AP sway increased (*high search-load only*) • **STS-ML, STS-AP, LTS-AP sway greater under dual-focus than cognitive task-focus instructions**	**Cognitive task performance decreased** • **RT decreased in narrow-base standing in dual-focus instruction condition *(high search-load only)***

EXP 2: Conjunction visual search (2 levels) in 3-D. All search items in world-frame or all search items in task-frame.	Young adults (*n* = 20)	Cognitive task-focus	**Posture sway increased** HEAD: • STS-ML, STS-AP, LTS-ML, LTS-AP sway increased (*high search-load only*) • **STS-AP sway greater in non-coincident than coincident frames** HIP: • STS-ML, STS-AP, LTS-ML, LTS-AP sway increased (*high search-load only*)	**Cognitive task performance decreased** • **RT decreased in non-coincident frames** (*high search-load only*) • **Errors increased in narrow-base standing in non-coincident frames** (*target-absent trials only*)
EXP 3: Conjunction visual search (2 levels) in 3-D. All search items in world-frame or all search items in task-frame.	Young adults (*n* = 19)	Dual-task focus	**Posture sway increased** HEAD: • STS-ML, STS-AP, LTS-ML, LTS-AP increased (*high search-load only*) • STS-ML, LTS-ML sway greater in narrow-base than wide-base standing (*high search-load only*) HIP: • STS-ML, STS-AP, LTS-ML, LTS-AP sway increased (*high search-load only*) • STS-ML, LTS-ML sway greater in narrow-base than wide-base standing (*high search-load only*) • **STS-AP, LTS-AP sway greater under non-coincident than coincident frames**	**Cognitive task performance unchanged**

.

EXP 4: Conjunction visual search (2 levels) in 3-D. Half of search items in world-frame and other half in task-frame.	Young adults ($n = 26$)	Cognitive task-focus	**Posture sway increased** HEAD: • STS-AP sway increased (*high search-load only*) • **STS-AP, LTS-AP† sway greater under non-coincident than coincident frames** HIP: • STS-AP sway increased (*high search-load only*) • **STS-ML† , STS-AP, LTS-ML, LTS-AP sway greater under non-coincident than coincident frames**	**Cognitive task performance unchanged**
EXP 5: Conjunction visual search (2 levels) in 3-D. Half of search items in world-frame and other half in task-frame.	Young adults ($n = 20$)	Dual-task focus	**Posture sway increased** HEAD: • **LTS-AP sway greater in non-coincident than coincident frames** (*high search-load only*) HIP: • STS-AP sway increased (*high search-load only*) • LTS-ML sway greater in narrow-base standing vs. wide-base (*high search-load only*) • **LTS-AP† sway greater in non-coincident than coincident frames** • **LTS-AP sway decreased in coincident frames** (*high search-load only*)	**Cognitive task performance unchanged**

EXP 6: Conjunction visual search (2 levels) in 2-D OR 3-D. Half of search items in world-frame and other half in task-frame. **Wide-base only.**	Young adults ($n = 24$)	Cognitive task-focus	**Postural sway increased** HEAD: • **STS-ML, LTS-ML sway increased in coincident frames** (*high search-load only*) HIP: • No effect	**Cognitive task performance unchanged**
EXP 7: Mental rotation task (3 levels) in 3-D. Both identity and parity/non-parity figures either in world-frame or both in task-frame.	Young adults ($n = 19$)	Cognitive task-focus	**Posture sway increased** HEAD: • STS-ML, LTS-ML sway greater in wide-base than narrow-base standing *(medium vs. low rotation-load*) • **STS-AP sway greater in narrow-base than wide-base standing in non-coincident frames** (*high rotation-load only*) • **STS-ML†, LTS-ML, LTS-AP sway greater in non-coincident than coincident frames** • STS-ML, STS-AP, LTS-ML, LTS-AP increased in narrow-base standing (*high rotation-load only*) HIP: • **STS-AP , LTS-ML†, LTS-AP sway greater in non-coincident than coincident frames**	**Cognitive task performance unchanged**

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Appendix: ANOVAs to the Results

Within-Participants ANOVAs

Experiment 1 *Visual search*

	ACCURACY					RT				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
TARGET	1,20	4.958E-03	18.824	< .001***	.485	1,20	4.284	171.636	< .001***	.896
INSTR	1,20	3.737E-03	.072	.792	.004	1,20	1.900E-04	.004	.950	.000
LOAD	1,20	4.009E-03	5.412	.031*	.213	1,20	19.999	212.876	< .001***	.914
STANCE	1,20	1.150E-03	.647	.431	.031	1,20	4.108E-03	.460	.505	.022
INSTR*STANCE	1,20	1.057E-03	.704	.411	.034	1,20	2.430E-02	.152	.152	.100
INSTR*LOAD	1,20	4.249E-03	.007	.934	.000	1,20	5.774E-03	.413	.528	.020
STANCE*LOAD	1,20	2.174E-03	.123	.729	.006	1,20	3.087E-03	.244	.627	.012
INSTR*STANCE*LOAD	1,20	1.205E-03	.222	.642	.011	1,20	3.988E-02	5.746	.026*	.223
INSTR*TARGET	1,20	3.007E-03	.990	.332	.047	1,20	4.454E-04	.109	.744	.005
STANCE*TARGET	1,20	2.254E-03	1.901	.183	.087	1,20	3.557E-03	1.368	.256	.064
INSTR*STANCE*TARGET	1,20	1.017E-03	1.000	.329	.048	1,20	9.023E-03	1.894	.184	.086
LOAD*TARGET	1,20	3.0 39E-03	10.029	.005**	.334	1,20	2.163	107.068	<. 001***	.843
INSTR*LOAD*TARGET	1,20	1.469E-03	.000	1.000	.000	1,20	3.572E-03	.596	.449	.029
STANCE*LOAD*TARGET	1,20	1.603E-03	.669	.423	.032	1,20	5.977E-04	.327	.574	.016
INSTR*STANCE*LOAD*TARG	1,20	2.057E-03	.058	.812	.003	1,20	6.697E-03	.944	.343	.045

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 1 *Posture sway, STS (Head)*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
INSTR	1,20	5.931E-04	6.438	.020*	.244	1,20	4.699E-05	7.021	.015*	.260
STANCE	1,20	1.253E-04	148.305	< .001***	.881	1,20	8.443E-05	24.119	< .001*	.547
LOAD	1,20	4.859E-04	8.022	.010**	.286	1,20	8.096E-05	10.525	.004**	.345
INSTR*LOAD	1,20	2.482E-04	.134	.719	.007	1,20	2.305E-05	.071	.793	.004
INSTR*STANCE	1,20	4.899E-04	.405	.532	.020	1,20	2.912E-05	.381	.544	.019
LOAD*STANCE	1,20	2.980E-05	3.092	.094	.134	1,20	2.695E-05	.552	.466	.027
INSTR*LOAD*STANCE	1,20	3.747E-04	.021	.887	.001	1,20	6.694E-04	1.377	.254	.064

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 1 *Posture sway, LTS (Head)*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
INSTR	1,20	5.683E-04	2.834	.108	.124	1,20	6.590E-04	6.258	.022*	.238
STANCE	1,20	1.372E-03	168.300	< .001***	.894	1,20	7.075E-04	19.446	< .001***	.493
LOAD	1,20	2.067E-04	6.262	.021*	.238	1,20	2.853E-03	19.879	.015*	.498
INSTR*LOAD	1,20	1.490E-08	.564	.462	.027	1,20	2.141E-04	.311	.583	.015
INSTR*STANCE	1,20	3.848E-04	.000	.984	.000	1,20	3.679E-04	.151	.702	.007
LOAD*STANCE	1,20	2.113E-04	3.165	.090	.137	1,20	3.679E-04	.147	.705	.007
INSTR*LOAD*STANCE	1,20	2.991E-04	.002	.967	.000	1,20	4.094E-04	.288	.598	.014

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001

Experiment 2 *Visual search*

	ACCURACY					RT				
	df	MSE	F-stat.	*p*	η^2_p	df	MSE	F-stat.	*p*	η^2_p
TARGET	1,21	6.350E-03	30.448	< .001***	.592	1,20	7.251E-02	115.794	< .001***	.846
FRAME	1,21	1.959E-03	.613	.443	.028	1,20	2.158E-02	3.787	.065	.153
LOAD	1,21	4.291E-03	22.655	< .001***	.519	1,20	.145	256.801	< .001***	.924
STANCE	1,21	1.329E-03	.048	829	.002	1,20	3.363E-02	.060	.809	.003
TARGET*FRAME	1,21	1.537E-03	.042	.840	.002	1,20	4.714E-03	2.792	.110	.117
TARGET*LOAD	1,21	2.968E-03	18.952	< .001***	.474	1,20	6.474E-02	77.879	< .001***	.788
FRAME*LOAD	1,21	1.361E-03	2.301	.144	.099	1,20	2.713E-02	5.302	.032*	.202
TARGET*FRAME*LOAD	1,21	2.435E-03	.236	.632	.011	1,20	8.012E-03	.600	.447	.028
TARGET*STANCE	1,21	1.570E-06	.005	.947	.000	1,20	1.325E-02	.019	.891	.001
FRAME*STANCE	1,21	1.242E-03	.006	.940	.000	1,20	2.223E-02	.385	.541	.018
TARGET*FRAME*STANCE	1,21	1.375E-03	4.345	.050*	.171	1,20	1.074E-02	2.666	.117	.113
LOAD*STANCE	1,21	2.564E-03	1.006	.327	.046	1,20	2.467E-02	.084	.775	.004
TARGET*LOAD*STANCE	1,21	1.781E-03	.674	.421	.031	1,20	1.698E-02	.006	.940	.000
FRAME*LOAD*STANCE	1,21	1.245E-03	.462	.504	.022	1,20	2.624E-02	1.910	.182	.083
TAR*FRAME*LOAD*STANCE	1,21	9.744E-04	.007	.933	.000	1.20	5.893E-03	.043	.838	.002

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 2 *Posture sway, STS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,21	3.383E-05	.008	.929	.000	1,21	3.783E-05	.088	.770	.004
LOAD	1,21	5.153E-05	17.756	< .001***	.458	1,21	4.298E-05	17.544	< .001***	.455
STANCE	1,21	8.184E-05	189.991	< .001***	.900	1,21	4.923E-05	22.028	< .001***	.512
FRAME*LOAD	1,21	4.884E-05	.623	.439	.029	1,21	3.364E-05	5.894	.024*	.219
FRAME*STANCE	1,21	3.259E-05	.870	.362	.040	1,21	4.090E-05	1.018	.324	.046
LOAD*STANCE	1,21	4.419E-05	.340	.566	.016	1,21	1.920E-05	1.298	.267	.058
FRAME*LOAD*STANCE	1,21	3.081E-05	.162	.691	.008	1,21	4.452E-05	.182	.674	.009

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 2 *Posture sway, LTS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,21	1.283E-04	.260	.616	.012	1,21	1.769E-04	.036	.852	.002
LOAD	1,21	5.001E-03	12.432	.002**	.372	1,21	2.939E-04	23.189	< .001***	.525
STANCE	1,21	9.688E-04	191.499	< .001***	.901	1,21	4.677E-04	13.021	.002**	.383
FRAME*LOAD	1,21	6.664E-04	.001	.978	.000	1,21	3.451E-04	1.310	.265	.059
FRAME*STANCE	1,21	4.271E-04	1.018	.324	.046	1,21	2.292E-04	.328	.573	.015
LOAD*STANCE	1,21	4.133E-04	.391	.538	.018	1,21	1.800E-04	.917	.349	.042
FRAME*LOAD*STANCE	1,21	3.500E-04	.413	.527	.019	1,21	2.216E-04	.268	.610	.013

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 2 *Posture sway, STS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,21	1.909E-05	.001	.979	.000	1,21	1.874E-05	.036	.852	.002
LOAD	1,21	2.662E-04	8.960	.007**	.299	1,21	2.591E-05	12.273	.002**	.369
STANCE	1,21	5.140E-05	146.939 .136	< .001***	.875	1,21	2.559E-05	44.348 1.048	< .001***	.679
FRAME*LOAD	1,21	2.529E-05	2.350	.716	.006	1,21	1.309E-05	1.111	.318	.048
FRAME*STANCE	1,21	2.781E-04	.692	.140	.101	1,21	1.704E-05	.317	.304	.050
LOAD*STANCE	1,21	2.330E-05	.397	.415	.032	1,21	1.793E-05	.923	.580	.015
FRAME*LOAD*STANCE	1,21	1.526E-05		.535	.019	1,21	2.044E-05		.348	.042

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 2 *Posture sway, LTS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,21	2.456E-04	.034	.855	.002	1,21	1.407E-03	.073	.789	.003
LOAD	1,21	2.454E-04	7.976	.010**	.275	1,21	2.412E-04	17.724	< .001***	.458
STANCE	1,21	5.618E-04	174.067	< .001***	.892	1,21	3.463E-04	18.214	< .001***	.464
FRAME*LOAD	1,21	3.354E-04	.020	.889	.001	1,21	2.382E-04	.256 1.496	.618	.012
FRAME*STANCE	1,21	2.372E-04	2.004	.172	.087	1,21	1.191E-04	.337	.235	.067
LOAD*STANCE	1,21	2.455E-04	.400	.534	.019	1,21	2.173E-04	.236	.568	.016
FRAME*LOAD*STANCE	1,21	1.745E-04	1.005	.328	.046	1,21	2.100E-04		.632	.011

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 3 *Visual search*

	ACCURACY					RT				
	df	MSE	F-stat.	*p*	η^2_p	df	MSE	F-stat.	*p*	η^2_p
TARGET	1,18	7.871E-03	33.852	< .001***	.653	1,18	4.783E-02	111.114	< .001***	.861
FRAME	1,18	2.354E-03	.056	.816	.003	1,18	2.421E-04	.005	.946	.000
LOAD	1,18	7.818E-03	21.812	< .001***	.548	1,18	21.5222	128.110	< .001***	.877
STANCE	1,18	3.042E-03	1.838	.192	.093	1,18	4.636E-04	.031	.861	.002
TARGET*FRAME	1,18	2.493E-03	.053	.821	.003	1,18	6.522E-03	.736	.402	.039
TARGET*LOAD	1,18	6.173E-03	32.419	< .001***	.643	1,18	3.455E-02	83.931	< .001***	.823
FRAME*LOAD	1,18	2.608E-03	.454	.509	.025	1,18	1.637E-03	.000	.984	.000
TARGET*FRAME*LOAD	1,18	2.853E-03	.184	.673	.010	1,18	1.390E-02	.330	.573	.018
TARGET*STANCE	1,18	1.943E-03	.017	.898	.001	1,18	4.722E-03	.013	.911	.001
FRAME*STANCE	1,18	8.224E-04	.340	.567	.019	1,18	1.238E-02	.135	.717	.007
TARGET*FRAME*STANCE	1,18	2.767E-03	.297	.592	.016	1,18	8.457E-03	1.266	.275	.066
LOAD*STANCE	1,18	1.276E-03	2.089	.166	.104	1,18	1.173E-02	.073	.791	.004
TARGET*LOAD*STANCE	1,18	3.077E-03	1.293	.270	.067	1,18	5.175E-03	.968	.338	.051
FRAME*LOAD*STANCE	1,18	1.595E-03	.021	.887	.001	1,18	1.320E-02	1.217	.285	.063
TAR*FRAME*LOAD*STANCE	1,18	4.424E-03	.364	.554	.020	1,18	7.347E-03	.726	.405	.039

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 3 *Posture sway, STS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,18	2.625E-05	2.391	.139	.117	1,18	1.398E-05	.879	.361	.047
LOAD	1,18	2.709E-05	16.055	.001***	.471	1,18	6.731E-05	16.000	.001***	.471
STANCE	1,18	7.324E-05	171.115	< .001***	.905	1,18	1.932E-06	34.082 .112	< .001***	.654
FRAME*LOAD	1,18	1.681E-05	2.610	.124	.127	1,18	1.729E-05	2.500	.742	.006
FRAME*STANCE	1,18	2.929E-05	.099	.757	.005	1,18	1.308E-05	.679	.131	.122
LOAD*STANCE	1,18	8.169E-05	4.590	.046*	.203	1,18	3.255E-05	.129	.421	.036
FRAME*LOAD*STANCE	1,18	1.536E-05	6.964	.017*	.279	1,18	3.533E-05		.724	.007

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 3 *Posture sway, LTS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,18	2.326E-04	.815	.379	.043	1,18	3.106E-04	3.692	.071	.170
LOAD	1,18	2.311E-04	12.513	.002**	.410	1,18	4.163E-04	13.088	.002**	.421
STANCE	1,18	6.136E-04	270.137	< .001***	.938	1,18	4.560E-04	10.194	.005**	.362
FRAME*LOAD	1,18	3.187E-04	.064	.803	.004	1,18	3.134E-04	.449	.511	.024
FRAME*STANCE	1,18	2.465E-04	.323	.577	.018	1,18	1.603E-04	.178	.678	.010
LOAD*STANCE	1,18	1.277E-04	6.945	.017*	.278	1,18	2.292E-04	.076	.786	.004
FRAME*LOAD*STANCE	1,18	3.233E-04	1.057	.318	.055	1,18	2.337E-04	.966	.339	.051

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 3 *Posture sway, STS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,18	1.274E-05	3.491	.078	.162	1,18	6.793E-06	4.654	.045*	.205
LOAD	1,18	1.508E-05	13.384	.002**	.426	1,18	1.861E-05	23.239	< .001***	.564
STANCE	1,18	4.494E-05	137.601	< .001***	.884	1,18	2.223E-06	27.411	< .001***	.604
FRAME*LOAD	1,18	6.591E-06	.411	.530	.022	1,18	6.475E-06	.692	.416	.037
FRAME*STANCE	1,18	1.647E-05	.029	.866	.002	1,18	5.302E-06	3.839	.066	.176
LOAD*STANCE	1,18	1.106E-05	7.136	.016*	.284	1,18	1.203E-05	.005	.945	.000
FRAME*LOAD*STANCE	1,18	1.130E-05	1.754	.202	.089	1,18	7.469E-06	.002	.964	.000

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 3 *Posture sway, LTS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,18	1.181E-04	2.073	.167	.103	1,18	6.904E-05	11.563	.003**	.391
LOAD	1,18	1.085E-04	9.797	.006**	.352	1,18	1.095E-04	20.378	< .001***	.531
STANCE	1,18	3.807E-04	245.983 .007	< .001***	.932	1,18	3.306E-04	15.574	.001***	.464
FRAME*LOAD	1,18	1.295E-04	.269	.935	.000	1,18	9.944E-05	.277	.605	.015
FRAME*STANCE	1,18	1.307E-04	9.694	.611	.015	1,18	6.469E-05	.058	.812	.003
LOAD*STANCE	1,18	5.913E-05	.577	.006**	.350	1,18	8.144E-05	.273	.608	.015
FRAME*LOAD*STANCE	1,18	1.802E-04		.457	.031	1,18	4.702E-05	.764	.394	.041

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 4 *Visual search*

	ACCURACY					RT				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
TARGET	1,25	54.502	34.544	< .001***	.580	1,25	5.566E-02	193.400 .752	< .001***	.886
FRAME	1,25	18.502	1.432	.243	.054	1,25	5.500E-02	230.119	.394	.029
LOAD	1,25	20.541	51.752	< .001***	.674	1,25	.178	.052	< .001***	.902
STANCE	1,25	19.502	.077	.784	.003	1,25	3.298E-02	.071	.822	.002
TARGET*FRAME	1,25	73.618	5.124	.033*	.170	1,25	1.599E-02	141.705	.792	.002
TARGET*LOAD	1,25	26.156	46.983	< .001***	.653	1,25	5.008E-02	.442	< .001***	.850
FRAME*LOAD	1,25	29.560	.002	.964	.000	1,25	2.387E-02	1.756	.512	.017
TARGET*FRAME*LOAD	1,25	28.752	.052	.821	.002	1,25	1.458E-02	1.078	.197	.066
TARGET*STANCE	1,25	23.695	2.762	.109	.099	1,25	1.430E-02	.061	.309	.041
FRAME*STANCE	1,25	21.002	.072	.791	.003	1,25	2.405E-02	.022	.806	.002
TARGET*FRAME*STANCE	1,25	18.810	.003	.955	.000	1,25	2.025E-02	.235	.884	.001
LOAD*STANCE	1,25	19.502	.077	.784	.003	1,25	2.643E-02	.146	.632	.009
TARGET*LOAD*STANCE	1,25	24.752	.061	.807	.002	1,25	1.258E-02	.380	.706	.006
FRAME*LOAD*STANCE	1,25	21.772	3.779	.063	.131	1,25	1.889E-02	.253	.543	.015
TAR*FRAME*LOAD*STANCE	1,25	16.445	1.319	.262	.050	1,25	1.908E-02		.619	.010

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 4 *Posture sway, STS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,25	3.519E-05	.322	.576	.013	1,25	3.562E-05	5.090	.033*	.169
LOAD	1,25	1.794E-05	.541	.469	.021	1,25	2.983E-05	9.463	.005**	.275
STANCE	1,25	9.739E-05	176.818	< .001***	.876	1,25	6.773E-05	16.397	< .001***	.396
FRAME*LOAD	1,25	3.066E-05	.013	.910	.001	1,25	3.803E-05	1.872	.183	.070
FRAME*STANCE	1,25	3.332E-05	.013	.911	.001	1,25	3.314E-05	.099	.756	.004
LOAD*STANCE	1,25	2.657E-05	.043	.838	.002	1,25	2.886E-05	.000	.985	.000
FRAME*LOAD*STANCE	1,25	2.014E-05	3.339	.080	.118	1,25	2.088E-05	1.153	.293	.044

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 4 *Posture sway, LTS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,25	3.441E-04	3.592	.070	.126	1,25	2.731E-04	4.120	.053	.141
LOAD	1,25	1.751E-04	2.886	.102	.103	1,25	2.948E-04	3.801	.063	.132
STANCE	1,25	1.093E-03	230.576	< .001***	.902	1,25	4.874E-04	19.775	< .001***	.442
FRAME*LOAD	1,25	2.152E-04	.070	.793	.003	1,25	2.935E-04	.994	.328	.038
FRAME*STANCE	1,25	2.088E-04	.073	.790	.003	1,25	2.256E-04	1.136	.297	.043
LOAD*STANCE	1,25	2.393E-04	.174	.680	.007	1,25	1.023E-04	.756	.393	.029
FRAME*LOAD*STANCE	1,25	2.191E-04	1.967	.173	.073	1,25	2.190E-04	.643	.430	.025

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 4 *Posture sway, STS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,25	4.330E-04	4.139	.053	.142	1,25	1.326E-04	7.843	.010**	.239
LOAD	1,25	1.547E-04	.707	.409	.202	1,25	9.272E-05	.094	.762	.004
STANCE	1,25	3.083E-04	30.794 .472	< .001***	.552	1,25	1.104E-04	8.154	.009**	.246
FRAME*LOAD	1,25	1.879E-04	.069	.498	.019	1,25	1.079E-04	.007	.934	.000
FRAME*STANCE	1,25	2.202E-04	3.209	.795	.003	1,25	6.626E-05	.107	.746	.004
LOAD*STANCE	1,25	1.030E-04	6.338	.085	.114	1,25	6.213E-05	1.591	.219	.060
FRAME*LOAD*STANCE	1,25	8.204E-05		.019*	.202	1,25	4.115E-05	3.621	.069	.127

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 4 *Posture sway, LTS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
					.296					
FRAME	1,25	2.938E-04	10.528	.003**	.001	1,25	1.911E-04	11.407	.002**	.313
LOAD	1,25	1.303E-04	0.15	.904	.867	1,25	1.203E-04	1.445	.241	.055
STANCE	1,25	9.267E-04	163.542	< .001***	.003	1,25	3.254E-04	27.993	< .001***	.528
FRAME*LOAD	1,25	2.306E-04	.072	.791	.000	1,25	1.868E-04	.583	.452	.023
FRAME*STANCE	1,25	2.656E-04	.003	.954	.065	1,25	2.371E-04	.035	.853	.001
LOAD*STANCE	1,25	1.548E-04	1.752	.198	.149	1,25	9.145E-05	.028	.868	.001
FRAME*LOAD*STANCE	1,25	1.679E-04	4.377	.047*		1,25	1.428E-04	.428	.519	.017

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 5 *Visual search*

	ACCURACY					RT				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
TARGET	1,19	151.299	24.540	< .001***	.564	1,19	9.037E-02 .138	93.389	< .001***	.831
FRAME	1,19	23.750	.474	.500	.024	1,19	.196	.075	.788	.004
LOAD	1,19	158.158	18.976	< .001***	.500	1,19	1.488E-02	162.066	< .001***	.895
STANCE	1,19	21.645	.058	.813	.003	1,19	3.031E-02	5.745	.027	.232
TARGET*FRAME	1,19	88.092	.227	.639	.012	1,19	6.838E-02	.045	.834	.002
TARGET*LOAD	1,19	100.987	15.163	.001***	.444	1,19	6.191E-02	72.101	< .001***	.791
FRAME*LOAD	1,19	19.589	.144	.709	.007	1,19	7.256E-06	.164	.690	.009
TARGET*FRAME*LOAD	1,19	68.339	1.0291	.323	.051	1,19	2.226E-02	.000	.987	.000
TARGET*STANCE	1,19	30.592	4.086	.058	.177	1,19	1.889E-02	5.820	.026*	.234
FRAME*STANCE	1,19	31.891	1.186	.290	.059	1,19	2.742E-03	.165	.689	.009
TARGET*FRAME*STANCE	1,19	39.720	.197	.662	.010	1,19	2.564E-02	.110	.744	.006
LOAD*STANCE	1,19	21.694	.014	.906	.001	1,19	2.359E-02	2.836 2.179	.109	.130
TARGET*LOAD*STANCE	1,19	40.444	.626	.439	.032	1,19	2.115E-02	1.537	.156	.103
FRAME*LOAD*STANCE	1,19	27.895	.045	.835	.002	1,19	2.451E-02	.533	.230	.075
TAR*FRAME*LOAD*STANCE	1,19	26.908	.046	.832	.002	1,19			.474	.027

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 5 *Posture sway, STS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,19	8.969E-06	.030	.865	.002	1,19	2.194E-05	.199	.661	.010
LOAD	1,19	2.589E-05	1.599	.221	.078	1,19	1.951E-05	1.078	.312	.054
STANCE	1,19	8.262E-05	162.574	< .001***	.895	1,19	1.467E-03	25.305	< .001***	.571
FRAME*LOAD	1,19	1.831E-05	.131	.721	.007	1,19	1.867E-05	3.062	.096	.139
FRAME*STANCE	1,19	1.256E-05	.707	.411	.036	1,19	1.392E-05	1.397	.252	.068
LOAD*STANCE	1,19	1.655E-05	.219	.645	.011	1,19	1.653E-05	.330	.572	.017
FRAME*LOAD*STANCE	1,19	1.296E-05	.070	.793	.004	1,19	3.137E-05	3.591	.073	.159

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 5 *Posture sway, LTS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,19	7.080E-05	.074	.788	.004	1,19	1.432E-04	1.317	.265	.065
LOAD	1,19	1.743E-04	.056	.816	.003	1,19	1.144E-04	.016	.901	.001
STANCE	1,19	1.188E-03	157.898	< .001***	.893	1,19	2.303E-04	48.601	< .001***	.719
FRAME*LOAD	1,19	7.646E-05	2.400	.138	.112	1,19	9.405E-05	6.808	.017*	.264
FRAME*STANCE	1,19	1.057E-04	2.802	.111	.129	1,19	2.626E-07	.002	.965	.000
LOAD*STANCE	1,19	2.047E-04	2.854	.107	.131	1,19	1.859E-04	1.004	.329	.050
FRAME*LOAD*STANCE	1,19	8.607E-05	.570	.459	.029	1,19	2.609E-04	.684	.418	.035

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 5 *Posture sway, STS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,19	1.977E-04	.560	.464	.029	1,19	2.208E-04	.284	.600	.015
LOAD	1,19	2.395E-05	1.781	.198	.086	1,19	1.352E-05	4.947	.038*	.207
STANCE	1,19	5.040E-05	164.321	< .001***	.896	1,19	3.121E-05	55.995	< .001**	.747
FRAME*LOAD	1,19	2.827E-05	.012	.914	.001	1,19	1.967E-05	.776	.389	.039
FRAME*STANCE	1,19	4.926E-05	.483	.496	.025	1,19	2.394E-05	1.655	.214	.080
LOAD*STANCE	1,19	1.859E-04	1.004	.329	.050	1,19	2.106E-05	.081	.779	.004
FRAME*LOAD*STANCE	1,19	4.420E-05	.676	.421	.034	1,19	2.360E-05	.791	.385	.040

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 5 *Posture sway, LTS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,19	1.122E-04	.543	.470	.020	1,19	9.347E-05	.174	.682	.009
LOAD	1,19	1.317E-04	.132	.720	.007	1,19	7.492E-05	.063	.805	.003
STANCE	1,19	6.385E-04	199.477	< .001*	.913	1,19	2.125E-04	50.684	< .001***	.727
FRAME*LOAD	1,19	4.828E-05	2.092	.164	.099	1,19	4.997E-05	9.246	.007**	.327
FRAME*STANCE	1,19	1.379E-04	.675	.422	.034	1,19	1.247E-04	.304	.588	.016
LOAD*STANCE	1,19	1.036E-04	7.725	.012*	.289	1,19	1.141E-04	.332	.571	.017
FRAME*LOAD*STANCE	1,19	6.170E-05	.002	.969	.000	1,19	1.905E-04	.991	.332	.050

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 6 *Visual search*

	ACCURACY					RT				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
TARGET	1,23	5.256E-03	31.317	< .001***	.577	1,23	7.328E-02	130.146	< .001***	.850
FRAME	1,23	3.240E-03	.098	.757	< .004	1,23	.120	.006	.938	.000
LOAD	1,23	2.409E-03	23.373	.001***	.504	1,23	9.000E-02	420.334	< .001***	.948
DEPTH	1,23	1.637E-03	.195	.663	.008	1,23	2.770E-02	11.073	.003**	.325
TARGET*FRAME	1,23	3.199E-03	.002	.964	.000	1,23	2.568E-02	.134	.718	.006
TARGET*LOAD	1,23	3.693E-03	19.436	< .001***	.458	1,23	3.860E-02	143.718	< .001***	.862
FRAME*LOAD	1,23	1.608E-03	1.786	.194	.072	1,23	4.364E-02	.323	.576	.014
TARGET*FRAME*LOAD	1,23	3.138E-03	.052	.822	.002	1,23	1.314E-02	.643	.431	.027
TARGET*DEPTH	1,23	1.465E-03	.360	.554	.015	1,23	1.002E-02	3.600	.070	.135
FRAME*DEPTH	1,23	3.469E-03	.017	.898	.001	1,23	3.422E-02	.546	.468	.023
TARGET*FRAME*DEPTH	1,23	1.764E-03	.299	.590	.013	1,23	1.284E-02	.211	.650	.009
LOAD*DEPTH	1,23	1.485E-03	.039	.844	.002	1,23	2.799E-02	4.408	.047*	.161
TARGET*LOAD*DEPTH	1,23	1.050E-03	.772	.389	.032	1,23	9.307E-03	.772	.389	.032
FRAME*LOAD*DEPTH	1,23	1.739E-03	.633	.434	.027	1,23	4.353E-02	.298	.590	.013
TAR*FRAME*LOAD*DEPTH	1,23	1.189E-03	5.264	.031*	.186	1,23	8.241E-03	2.388	.136	.094

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 6 *Posture sway, STS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,23	6.177E-05	.047	.831	.002	1,23	6.622E-05	.507	.484	.022
LOAD	1,23	6.124E-05	.022	.882	.001	1,23	4.251E-05	1.428	.244	.058
DEPTH	1,23	3.768E-05	.355	.557	.015	1,23	7.212E-05	.175	.679	.008
FRAME*LOAD	1,23	3.419E-05	5.771	.025*	.201	1,23	9.216E-05	1.312	.264	.054
FRAME*DEPTH	1,23	4.189E-05	.084	.775	.004	1,23	1.164E-04	.290	.595	.012
LOAD*DEPTH	1,23	4.998E-05	1.664	.210	.067	1,23	8.230E-05	.790	.383	.033
FRAME*LOAD*DEPTH	1,23	4.667E-05	.172	.682	.007	1,23	6.313E-05	.008	.930	.000

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 6 *Posture sway, LTS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,23	5.916E-04	.007	.933	.000	1,23	3.566E-04	.966	.336	.040
LOAD	1,23	3.041E-04	.072	.791	.003	1,23	1.917E-04	.720	.405	.030
DEPTH	1,23	1.592E-04	1.181	.288	.049	1,23	1.074E-04	.031	.862	.001
FRAME*LOAD	1,23	1.925E-04	4.411	.047*	.161	1,23	1.834E-04	.855	.365	.036
FRAME*DEPTH	1,23	1.886E-04	.257	.617	.011	1,23	2.039E-04	.491	.490	.021
LOAD* DEPTH	1,23	2.557E-04	.421	.523	.018	1,23	1.901E-04	.499	.487	.021
FRAME*LOAD* DEPTH	1,23	1.759E-04	.264	.612	.011	1,23	2.485E-04	.149	.703	.006

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 6 *Posture sway, STS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η^2_p	df	MSE	F-stat.	*p*	η^2_p
FRAME	1,23	6.461E-05	.001	.973	.000	1,23	2.462E-05	1.388	.251	.057
LOAD	1,23	4.651E-05	.000	.995	.000	1,23	3.453E-05	3.216.	.086	.123
DEPTH	1,23	4.327E-05	1.749	.199	.071	1,23	2.111E-05	.866	.362	.036
FRAME*LOAD	1,23	4.312E-05	2.543	.124	.100	1,23	3.926E-05	1.560	.224	.064
FRAME*DEPTH	1,23	3.588E-05	.157	.696	.007	1,23	2.813E-05	.140	.711	.006
LOAD*DEPTH	1,23	3.726E-05	1.974	.173	.079	1,23	2.113E-05	.077	.784	.003
FRAME*LOAD*DEPTH	1,23	4.373E-05	.272	.607	.012	1,23	1.941E-05	.010	.920	.000

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 6 *Posture sway, LTS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η^2_p	df	MSE	F-stat.	*p*	η^2_p
FRAME	1,23	5.433E-04	.009	.925	.000	1,23	3.542E-04	.331	.570	.014
LOAD	1,23	5.364E-0	.565	.460	.024	1,23	1.188E-04	.911	.350	.038
DEPTH	1,23	1.897E-04	.835	.370	.035	1,23	1.501E-04	.123	.729	.005
FRAME*LOAD	1,23	4.661E-04	2.850	.105	.110	1,23	1.255E-04	1.393	.250	.057
FRAME*DEPTH	1,23	1.482E-04	.489	.491	.021	1,23	2.051E-04	.076	.785	.003
LOAD* DEPTH	1,23	2.188E-04	.000	.999	.000	1,23	2.248E-04	.951	.340	.040
FRAME*LOAD* DEPTH	1,23	1.618E-04	.494	.489	.021	1,23	1.715E-04	.473	.498	.020

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 7 *Mental Rotation*

	ACCURACY					RT				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
JUDGMENT	1,18	22145.316	32.683	< .001***	.645	1,18	115.019	55.843	< .001***	.756
FRAME	1,18	131.037	.534	.474	.029	1,18	.870	.388	.541	.021
ROTATION	1,18	27736.067	62.210	< .001***	.776	1,18	67.180	41.938	< .001***	.700
STANCE	1,18	69.309	.425	.523	.023	1,18	1.295	1.188	.290	.062
JUDGE*FRAME	1,18	8.093E-10	.000	1.000	.003	1,18	8.47E-03	.009	.924	.001
JUDGE*ROTATION	1,18	13.266	.049	.952	.000	1,18	1.312	1.490	.239	.076
FRAME*ROTATION	1,18	484.351	2.146	.132	.107	1,18	.289	.133	.876	.007
JUDGE*FRAME*ROTATION	1,18	283.463	2.324	.112	.114	1,18	.320	.584	.563	.031
JUDGE*STANCE	1,18	572.882	3.251	.088	.153	1,18	3.903E-02	.038	.847	.003
FRAME*STANCE	1,18	1.083	.005	.944	.000	1,18	.284	.510	.484	.028
JUDGE*FRAME*STANCE	1,18	155.945	1.046	.320	.055	1,18	5.795E-0	.110	.744	.006
ROTATION*STANCE	1,18	125.353	1.103	.343	.058	1,18	1.836	2.789	.075	.006
JUDGE*ROTATION*STANCE	1,18	256.931	1.988	.150	.100	1,18	.480	.651	.528	.134
FRAME*ROTATION*STANCE	1,18	159.465	.488	.618	.072	1,18	.665	.826	.446	044
JUD*FRAME*ROT*STANCE	1,18	137.265	1.391	.262	.026	1,18	5.168E-02	.122	.886	.007

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 7 *Posture sway, STS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,18	6.152E-05	4.266	.054	.192	1,18	3.732E-05	1.759	.201	.089
ROTATION	1,18	1.778E-05	.904	.414	.048	1,18	3.194E-05	2.588	.091	.125
STANCE	1,18	1.422E-04	214.108	< .001***	.922	1,18	5.978E-05	20.277	< .001**	.532
FRAME*ROTATION	1,18	2.799E-05	2.337	.144	.115	1,18	4.174E-05	.415	.611	.023
FRAME*STANCE	1,18	3.703E-05	.557	.457	.031	1,18	2.430E-05	.164	.691	.009
ROTATION*STANCE	1,18	1.145E-05	3.767	.033*	.173	1,18	5.562E-05	.531	.588	.029
FRAME*ROTATION* STANCE	1,18	1.166E-03	.177	.801	.010	1,18	2.024E-05	3.739	.033*	.172

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 7 *Posture sway, LTS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,18	8.851E-04	5.388	.032*	.230	1,18	3.311E-03	7.129	.016*	.284
ROTATION	1,18	5.468E-04	.310	.736	.017	1,18	3.395E-04	1.056	.358	.055
STANCE	1,18	9.342E-04	192.969	< .001**	.915	1,18	9.439E-05	12.051	.003**	.401
FRAME*ROTATION	1,18	6.280E-05	2.589	.105	.126	1,18	8.558E-03	.274	.762	.015
FRAME*STANCE	1,18	4.168E-05	1.012	.328	.053	1,18	4.921E-05	.221	.644	.012
ROTATION*STANCE	1,18	4.096E-04	4.401	.031*	.196	1,18	1.640E-04	.302	.741	.016
FRAME*ROTATION* STANCE	1,18	3.802E-04	.680	.495	.036	1,18	2.880E-04	1.737	.191	.088

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 7 *Posture sway, STS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,18	5.085E-05	2.261	.150	.112	1,18	2.283E-05	5.139	.036*	.222
ROTATION	1,18	3.552E-05	.084	.920	.005	1,18	2.282E-05	.279	.758	.015
STANCE	1,18	1.052E-04	67.039	< .000***	.788	1,18	7.980E-05	7.998	.011*	.308
FRAME*ROTATION	1,18	4.864E-05	1.169	.322	.061	1,18	4.110E-05	.831	.762	.044
FRAME*STANCE	1,18	2.551E-05	1.025	.325	.054	1,18	9.422E-06	.000	.644	.000
ROTATION*STANCE	1,18	6.488E-05	1.595	.217	.081	1,18	4.566E-05	.681	.741	.036
FRAME*ROTATION* STANCE	1,18	6.606E-05	1.278	.291	.066	1,18	1.481E-05	2.001	.191	.100

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiment 7 *Posture sway, LTS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
FRAME	1,18	6.309E-04	3.970	.062	.181	1,18	1.201E-03	5.429	.032*	.232
ROTATION	1,18	2.792E-06	.279	.758	.015	1,18	1.852E-03	.713	.497	.038
STANCE	1,18	9.853E-04	79.217	< .001***	.815	1,18	2.304E-03	3.333	.085	.156
FRAME*ROTATION	1,18	8.768E-05	2.240	.140	.011	1,18	1.565E-03	.444	.605	.024
FRAME*STANCE	1,18	3.853E-04	.143	.709	.008	1,18	1.003E-03	.780	.389	.042
ROTATION*STANCE	1,18	3.207E-04	2.663	.113	.129	1,18	2.085E-03	1.355	.267	.070
FRAME*ROTATION* STANCE	1,18	6.944E-04	1.115	.313	.058	1,18	1.728E-03	.930	.358	.049

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Between-Participants ANOVAs

Experiments 2-3 *Visual search*

	ACCURACY					RT				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
INSTR	1,39	1.315E-02	3.557	0.67	0.84	1,39	.451	.612	.439	.015
TARGET	1,39	.459	65.079	< .001***	.625	1,39	13.652	218.356	< .001***	.848
TARGET*INSTR	1,39	-	.880	.354	.022	1,39	-	.411	.525	.010
FRAME	1,39	2.305E-04	.108	.745	.003	1,39	4.837E-02	.2083	.157	.051
FRAME*INSTR	1,39	-	.478	.494	.012	1,39	-	.478	.494	.012
LOAD	1,39	.265	44.766	< .001***	.534	1,39	58.351	360.426	< .001***	.902
LOAD*INSTR	1,39	-	1.376	.248	.034	1,39	-	1.999	.165	.049
STANCE	1,39	3.607E-03	1.708	.199	.042	1,39	2.491E-03	.101	.752	.003
STANCE*INSTR	1,39	-	1.145	.291	.029	1,39	-	.364	.550	.009
TARGET*FRAME	1,39	1.917E-04	.097	.757	.002	1,39	1.594E-03	.286	.596	.007
TARGET*FRAME*INSTR	1,39	-	.004	.947	.000	1,39	-	2.821	.101	.067
TARGET*LOAD	1,39	.239	53.800	< .001**	.580	1,39	7.877	150.369	< .001***	.794
TARGET*LOAD*INSTR	1,39	-	6.213	.017*	.137	1,39	-	.332	.568	.008
FRAME*LOAD	1,39	1.662E-04	0.86	.771	.002	1,39	8.019E-02	3.447	.071	.081
FRAME*LOAD*INSTR	1,39	-	2.069	.158	.050	1,39	-	.974	.330	.024
TARGET*FRAME*LOAD	1,39	2.279E-07	.000	.993	.000	1,39	7.818E-05	.008	.931	.000
TARG*FRAME*LOAD*INSTR	1,39	-	.418	.552	.011	1,39	-	2.783	.103	.067
TARGET*STANCE	1,39	5.698E-06	.003	.955	.000	1,39	3.350E-04	.036	.850	.001
TARGET*STANCE*INSTR	1,39	-	.021	.886	.001	1,39	-	.312	.580	.001
FRAME*STANCE	1,39	3.683E-04	.206	.652	.005	1,39	1.985E-03	.117	.734	.003
FRAME*STANCE*INSTR	1,39	-	.292	.592	.007	1,39	-	2.075	.158	.051
TARGET*FRAME*STANCE	1,39	9.989E-04	4952	.486	.013	1,39	3.040E-03	.289	.594	.007
TAR*FRAME*STANCE*INST	1,39	-	.687	.109	.064	1,39	-	.444	.509	.011
LOAD*STANCE	1,39	5.225E-03	2.664	.111	.064	1,39	1.592E-04	.008	.927	.000
LOAD*STANCE*INSTR	1,39	-	.006	.940	.000	1,39	-	.072	.790	.002
TARGET*LOAD*STANCE	1,39	5.121E-04	.215	.645	.005	1,39	3.331E-03	.288	.595	.007
TAR*LOAD*STANCE*INSTR	1,39	-	2.048	.160	.050	1,39	-	.300	.587	.008
FRAME*LOAD*STANCE	1,39	4.214E-04	.300	.587	.008	1,39	7.207E-04	.370	.547	.009
FRA*LOAD*STANCE*INSTR	1,39	-	.105	.748	.003	1,39	-	4.563	.039*	.105
TARGET*LOAD*STANCE	1,39	9.749E-04	.380	541	.010	1,39	3.421E-04	.547	.464	.014
TAR*LOAD*STANCE*FRAME*INST	1,39	-	.297	589	.008	1,39	-	2.190	.147	.053

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiments 2-3 *Posture sway, STS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η^2_p	df	MSE	F-stat.	*p*	η^2_p
INSTR	1,39	2.305E-04	.143	.707	.004	1,39	3.798E-04	.297	.589	.008
FRAME	1,39	2.975E-05	1.073 3.494	.307	.027	1,39	1.504E-04	.542	.466	.014
FRAME*INSTR	1,39	-	33.356	.069	.082	1,39	-	.000	.998	.000
LOAD	1,39	1.332E-02	1.015	< .001***	.461	1,39	1.780E-02	34.172	<.001***	.467
LOAD*INSTR	1,39	-	379.021	.320	.025	1,39	-	2.130	.152	.052
STANCE	1,39	2.816E-06	1.996 2.138	< .001***	.907	1,39	2.274E-06	52.960 .107	< .001***	.576
STANCE*INSTR	1,39	-	1.520	.167	.048	1,39	-	4.962	.745	.003
FRAME*LOAD	1,39	7.015E-05	.824	.152	.052	1,39	1.311E-05	2.320	.032*	.113
FRAME*LOAD*INSTR	1,39	-	.004	.225	.038	1,39	-	.824	.225	.038
FRAME*STANCE	1,39	4.987E-05	2.477	.369	.021	1,39	2.573E-05	3.175	.136	.056
FRAME*STANCE*INSTR	1,39	-	1.119	.947	.000	1,39	-	.014	.841	.001
LOAD*STANCE	1,39	8.008E-05	.297	.124	.060	1,39	3.488E-05	1.119	.908	.000
LOAD*STANCE*INSTR	1,39	-	2.397	.748	.003	1,39	-	.011	.748	.003
FRAME*LOAD*STANCE	1,39	2.719E-05		.297	.028	1,39	4.492E-05	.064	.917	.000
FRA*LOAD*STANCE*INSTR	1,39	-		.130	.058	1,39	-		.802	.002

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiments 2-3 *Posture sway, LTS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
INSTR	1,39	1.830E-03	1.060	.310	.026	1,39	3.581E-03	.344	.561	.009
FRAME	1,39	2.970E-04	.813	.371	.020	1,39	4.161E-04	1.822	.185	.045
FRAME*INSTR	1,39	-	.860	.359	.020	1,39	-	2.946	.094	.070
LOAD	1,39	7.902E-02	25.156	< .001***	.392	1,39	1.220E-02	35.054	< .001***	.473
LOAD*INSTR	1,39	-	1.382	.247	.034	1,39	-	.276	.602	.007
STANCE	1,39	.352	444.956	< .001***	.919	1,39	1.074E-02	23.240	< .001***	.373
STANCE*INSTR	1,39	-	.739	.395	.019	1,39	-	.032	.859	.001
FRAME*LOAD	1,39	7.995E-05	.017	.898	.000	1,39	1.020E-05	.175	.678	.004
FRAME*LOAD*INSTR	1,39	-	2.092	.156	.051	1,39	-	.299	.588	.008
FRAME*STANCE	1,39	9.218E-05	2.651	.112	.064	1,39	8.669E-06	.044	.835	.001
FRAME*STANCE*INSTR	1,39	-	.266	.609	.007	1,39	-	.451	.506	.011
LOAD*STANCE	1,39	8.730E-05	3.054	.088	.073	1,39	1.548E-05	.766	.387	.019
LOAD*STANCE*INSTR	1,39	-	.007	.933	.000	1,39	-	.299	.587	.008
FRAME*LOAD*STANCE	1,39	9.837E-05	.030	.864	.001	1,39	2.495E-05	1.095	.302	.027
FRA*LOAD*STANCE*INSTR	1,39	-	2.049	.160	.050	1,39	-	.038	.847	.001

Asterisks confirm the outcome of repeated measures ANOVA (* p =<.05; ** p =<.01; *** p =<.001)

Experiments 2-3 *Posture sway, STS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
INSTR	1,39	1.37E-04	.082	.776	.002	1,39	2.291E-04	1.539	.222	.038
FRAME	1,39	1.814E-04	1.073	.282	.030	1,39	1.897E-05	1.425	.240	.035
FRAME*INSTR	1,39	-	3.987	.053	.093	1,39	-	.693	.410	.017
LOAD	1,39	4.407E-07	20.699	< .001***	.347	1,39	7.335E-07	33.171	< .001***	.460
LOAD*INSTR	1,39	-	.012	.913	.000	1,39	-	1.205	.279	.030
STANCE	1,39	1.378E-06	297.153	< .001***	.844	1,39	1.729E-06	71.773	< .001**	.648
STANCE*INSTR	1,39	-	1.779	.190	.044	1,39	-	.893	.351	.022
FRAME*LOAD	1,39	1.597E-05	.349	.558	.009	1,39	1.713E-05	1.704	.199	.042
FRAME*LOAD*INSTR	1,39	-	.982	.328	.025	1,39	-	.044	.836	.001
FRAME*STANCE	1,39	2.141E-05	1.444	.237	.036	1,39	8.726E-05	.008	.930	.000
FRAME*STANCE*INSTR	1,39	-	.483	.491	.012	1,39	-	3.375	.074	.080
LOAD*STANCE	1,39	8.012E-05	4.461	.041*	.103	1,39	3.733E-05	4.461	.245	.006
LOAD*STANCE*INSTR	1,39	-	.123	.728	.003	1,39	-	.041	.840	.001
FRAME*LOAD*STANCE	1,39	1.255E-06	.093	.762	.002	1,39	9.909E-06	.679	.415	.017
FRA*LOAD*STANCE*INSTR	1,39	-	1.501	.228	.037	1,39	-	.295	.590	.008

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiments 2-3 *Posture sway, LTS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
INSTR	1,39	1.210E-03	1.293	.262	.032	1,39	2.308E-03	2.887	.097	.069
FRAME	1,39	1.504E-04	.844	.364	.021	1,39	2.611E-04	2.645	.112	.064
FRAME*INSTR	1,39	-	2.398 16.985	.130	.058	1,39	-	4.654	.035*	.185
LOAD	1,39	2.146E-04		< .001***	.202	1,39	6.417E-07	35.132	< .001***	.474
LOAD*INSTR	1,39	-	1.208	279	.030	1,39	-	.059	.809	.002
STANCE	1,39	.191	401.294	< .001***	.911	1,39	1.144E-02	33.742	< .001***	.464
STANCE*INSTR	1,39	-	.352	.556	.009	1,39		.002	.964	.000
FRAME*LOAD	1,39	4.200E-04	.018	893	.000	1,39	4.168E-06	.024	.878	.001
FRAME*LOAD*INSTR	1,39	-	1.717	.198	.042	1,39	-	.109	.743	.003
FRAME*STANCE	1,39	4.078E-05	2.156	.150	.052	1,39	7.499E-05	.790	.380	.020
FRAME*STANCE*INSTR	1,39	-	.352	.557	.009	1,39	-	.764	.338	.019
LOAD*STANCE	1,39	5.518E-05	3.399	.073	.080	1,39	1.107E-05	.072	.790	.002
LOAD*STANCE*INSTR	1,39	-	.031	.861	.001	1,39	-	.815	.372	.020
FRAME*LOAD*STANCE	1,39	1.024E-05	.058	.810	.001	1,39	1.726E-05	.013	.910	.000
FRA*LOAD*STANCE*INSTR	1,39	-	1.917	.174	.047	1,39	-	.744	.394	.019

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiments 4-5 *Visual search*

	ACCURACY					RT				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
INSTR	1,44	1.315E-02	7.117	< .011*	.139	1,44	.451	.002	.962	.000
TARGET	1,44	57.512	57.512	< .001***	.567	1,44	18.900	267.529	< .001***	.859
TARGET*INSTR	1,44	-	3.072	.087	.065	1,44	-	.006	.938	.000
FRAME	1,44	.762	1.685	.201	.037	1,44	3.337E-03	.037	.849	.001
FRAME*INSTR	1,44	-	.037	.849	.001	1,44	-	.487	.489	.011
LOAD	1,44	387.626	49.139	< .001***	.528	1,44	71.367	385.040	< .001***	.897
INSTR*LOAD	1,44	-	4.847	.033*	.099	1,44	-	.002	.964	.000
STANCE	1,44	1.054E-03	2.718	.717	.000	1,44	6.102E-02	2.425	.127	.052
STANCE*INSTR	1,44	-	.000	.994	.003	1,44	-	1.475	.231	.032
TARGET*FRAME	1,44	81.356	.114	.707	.038	1,44	2.512E-03	.113	.738	.003
TARGET*FRAME*INSTR	1,44	-	1.761	.191	.039	1,44	-	.001	.970	.000
TARGET*LOAD	1,44	39.742	47.202	< .001*	.518	1,44	11.737	202.418	< .001***	.821
TARGET*LOAD*INSTR	1,44	-	.680	.414	.001	1,44	-	.131	.719	.003
FRAME*LOAD	1,44	2.023	.048	.828	.002	1,44	2.063E-02	.512	.478	.012
FRAME*LOAD*INSTR	1,44	-	.080	.778	.015	1,44	-	.002	.968	.000
TARGET*FRAME*LOAD	1,44	50.585	.659	.421	.024	1,44	1.071E-02	.538	.467	.012
TARG*FRAME*LOAD*INSTR	1,44	-	1.103	.229	.008	1,44	-	.581	.450	.013
TARGET*STANCE	1,44	188.780	.354	.555	.025	1,44	3.563E-02	2.009	.163	.044
TARGET*STANCE*INSTR	1,44	-	7.078	.011*	.139	1,44	-	7.074	.011*	.137
FRAME*STANCE	1,44	14.553	1.148	.290	.013	1,44	2.774E-04	.013	.651	.000
FRAME*STANCE*INSTR	1,44	-	.566	.456	.004	1,44	-	.208	.911	.005
TARGET*FRAME*STANCE	1,44	3.763	.184	.670	.003	1,44	6.511E-03	.029	.865	.001
TAR*FRAME*STANCE*INST	1,44	-	.135	.715	.002	1,44	-	.127	.723	.003
LOAD*STANCE	1,44	.074	.787	.932	.000	1,44	2.274E-02	.872	.365	.019
LOAD*STANCE*INSTR	1,44	-	.007	.418	.015	1,44	-	2.487	.122	.053
TARGET*LOAD*STANCE	1,44	21.07	.668	.599	.006	1,44	2.022E-02	1.167	.286	.026
TAR*LOAD*STANCE*INSTR	1,44	-	.281	.304	.024	1,44	-	2.277	.138	.049
LOAD*STANCE	1,44	26.422	1.082	.174	.042	1,44	3.665E-02	1.845	.181	.040
LOAD*STANCE*INSTR	1,44	-	1.906	.398	.016	1,44	-	.320	.575	.007
TARGET*LOAD*STANCE	1,44	15.302	730	.629	.005	1,44	1.736E-03	.811	.373	.018
TAR*LOAD*STANCE*FRAME*INST	1,44	-	.237			1,44	-	.075	.785	.002

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiments 4-5 *Posture sway, STS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
INSTR	1,44	2.187E-04	1.753	.192	.038	1,44	2.821E-04	.163	.688	.004
FRAME	1,44	6.790E-06	.284	.596	.006	1,44	1.029E-04	3.674	.062	.077
FRAME*INSTR	1,44	-	.140	.710	.003	1,44	-	1.797	.187	.039
LOAD	1,44	3.350E-06	.362	.550	.008	1,44	5.823E-06	2.295	.137	.050
LOAD*INSTR	1,44	-	2.222	.143	.048	1,44	-	8.317	.006**	.159
STANCE	1,44	3.016E-02	331.358	< .001***	.883	1,44	3.016E-02	331.358	< .001***	.883
STANCE*INSTR	1,44	-	.004	.950	.000	1,44	-	.732	.397	.016
FRAME*LOAD	1,44	3.638E-07	.099	.755	.002	1,44	1.265E-04	2.264	.045*	.088
FRAME*LOAD*INSTR	1,44	-	.022	.882	.001	1,44	-	.000	.983	.000
FRAME*STANCE	1,44	9.561E-06	.359	.667	.008	1,44	4.507E-06	.181	.672	.004
FRAME*STANCE*INSTR	1,44	-	.188	.552	.004	1,44	-	.818	.371	.019
LOAD*STANCE	1,44	5.342E-07	.024	.878	.001	1,44	2.843E-06	.121	.730	.003
LOAD*STANCE*INSTR	1,44	-	1.290	.653	.028	1,44	-	.141	.709	.003
FRAME*LOAD*STANCE	1,44	2.198E-05	2.202	.145	.048	1,44	2.250E-05	4.950	.352	.101
FRA*LOAD*STANCE*INSTR	1,44	-	.204	.262	.005	1,44	-	.886	.330	.028

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiments 4-5 *Posture sway, LTS, Head*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
INSTR	1,44	1.874E-03	.163	.689	.004	1,44	3.206E-03	.731	.397	.016
FRAME	1,44	2.261E-04	2.037	.161	.044	1,44	1.053E-03	8.317	.008*	.159
FRAME*INSTR	1,44	-	2.743	.105	.059	1,44	-	.641	.428	.014
LOAD	1,44	2.948E-04	1.686	.201	.037	1,44	5.328E-04	2.456	.124	.053
LOAD*INSTR	1,44	-	.891	.350	.020	1,44	-	2.045	.160	.044
STANCE	1,44	.431	380.218	< .001***	.896	1,44	2.081E-02	55.301	< .001***	.557
STANCE*INSTR	1,44	-	.025	.875	.001	1,44	-	.582	.450	.014
FRAME*LOAD	1,44	1.624E-04	1.046	.312	.023	1,44	9.174E-04	4.423	.593	.091
FRAME*LOAD*INSTR	1,44	-	.374	.544	.008	1,44	-	.290	.460	.007
FRAME*STANCE	1,44	2.405E-04	1.463	.233	.032	1,44	1.035E-04	.556	.427	.012
FRAME*STANCE*INSTR	1,44	-	.655	.423	.015	1,44	-	.643	.707	.014
LOAD*STANCE	1,44	1.937E-04	.863	.358	.019	1,44	1.983E-05	.144	.179	.003
LOAD*STANCE*INSTR	1,44		2.242	.141	.048	1,44	-	1.866	.252	.041
FRAME*LOAD*STANCE	1,44	3.594E-04	2.223	.143	.048	1,44	3.193E-04	1.347	.427	.030
FRA*LOAD*STANCE*INSTR	1,44	-	.439	.151	.010	1,44	-	.021	.886	.000

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiments 4-5 *Posture sway, STS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
INSTR	1,44	5.701E-04	.211	.648	.005	1,44	3.902E-04	.319	.575	.007
FRAME	1,44	4.002E-04	1.208	.278	.027	1,44	2.343E-04	1.373	.248	.030
FRAME*INSTR	1,44	-	3.872	.055	.081	1,44	-	4.341	.043*	.090
LOAD	1,44	1.293E-04	1.418	.240	.031	1,44	1.765E-05	.302	.586	.007
LOAD*INSTR	1,44	-	.040	.842	.001	1,44	-	1.120	.296	.025
STANCE	1,44	1.760E-02	89.378	< .001***	.670	1,44	2.623E-03	34.421	< .001***	.439
STANCE*INSTR	1,44	-	.089	.767	.002	1,44	-	1.780	.189	.039
FRAME*LOAD	1,44	3.333E-05	.280	.599	.006	1,44	5.580E-06	.080	.779	.002
FRAME*LOAD*INSTR	1,44	-	.371	.546	.008	1,44	-	.177	.676	.004
FRAME*STANCE	1,44	3.882E-05	.265	.928	.000	1,44	8.854E-06	.185	.670	.004
FRAME*STANCE*INSTR	1,44	-	.008	.609	.006	1,44	-	.699	.354	.020
LOAD*STANCE	1,44	4.008E-05	.529	.471	.012	1,44	3.105E-05	1.280	.407	.016
LOAD*STANCE*INSTR	1,44	-	4.105	.049*	.085	1,44	-	.686	.262	.028
FRAME*LOAD*STANCE	1,44	3.666E-04	1.817	.185	.040	1,44	2.304E-05	.878	.412	.015
FRA*LOAD*STANCE*INSTR	1,44	-	1.393	.203	.031	1,44	-	3.802	.058	.080

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)

Experiments 4-5 *Posture sway, LTS, Hip*

	ML					AP				
	df	MSE	F-stat.	*p*	η_p^2	df	MSE	F-stat.	*p*	η_p^2
INSTR	1,44	1.245E-03	.047	.830	.001	1,44	2.525E-03	.087	.770	.002
FRAME	1,44	9.489E-04	4.406	.042*	.091	1,44	1.143E-03	7.677	.008**	.105
FRAME*INSTR	1,44	-	8.403	.006**	.160	1,44	-	5.173	.028*	.149
LOAD	1,44	4.919E-06	.038	.847	.001	1,44	4.988E-0	.495	.485	.011
LOAD*INSTR	1,44	-	.125	.725	.003	1,44	-	1.058	.309	.033
STANCE	1,44	.276	343.569	< .001***	.886	1,44	1.987E-02	71.820	< .001***	.620
STANCE*INSTR	1,44	-	.168	.684	.004	1,44	-	.824	.369	.018
FRAME*LOAD	1,44	2.376E-06	.156	.694	.004	1,44	8.609E-05	.674	.416	.015
FRAME*LOAD*INSTR	1,44	-	.690	.411	.015	1,44	-	4.158	.047*	.086
FRAME*STANCE	1,44	4.396E-05	.209	.650	.005	1,44	7.409E-06	.039	.844	.001
FRAME*STANCE*INSTR	1,44	-	.295	.590	.007	1,44	-	.226	.637	.005
LOAD*STANCE	1,44	1.084E-05	.817	.371	.018	1,44	3.230E-05	.319	.575	.007
LOAD*STANCE*INSTR	1,44	-	7.780 2.686	.008*	.150	1,44	-	.126	.724	.003
FRAME*LOAD*STANCE	1,44	3.279E-04	2.551	.108	.058	1,44	2.397E-04	1.467	.232	.032
FRA*LOAD*STANCE*INSTR	1,44	-		.117	.055	1,44	-	.164	.688	.004

Asterisks confirm the outcome of repeated measures ANOVA (* *p* =<.05; ** *p* =<.01; *** *p* =<.001)