Task parameters shape goal-directed movement performance under dual-task conditions

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2016

Thesis submitted for the degree of Doctorate of Philosophy

Table of Contents

Abstract

Goal-directed movements are an important part of daily life. The conditions under which they are enacted can influence the success of these fine motor movements. Primarily this thesis aims to investigate the impact that changes in visual attention, created by dividing attention, have on pointing movements. All studies used a novel experimental design consisting of a central alphanumeric search presented with a concurrent pointing task. This design required the division of attention between central and peripheral vision. In order to assess the participant's performance of these tasks, data on several outcome measures were obtained. The pointing endpoint yielded a measure of movement accuracy (or how far the touch was from the target) and how variable the movement endpoint was (precision). Movement time was divided into two sections; the movement latency (ML) or the time between target onset and movement commencement and reach time (RT) the time the hand was in flight. Additionally participant responses to the search task were measured.

In study one dual-task performance of a cognitive and motor task was used to assess the effect of the presence or absence of attentional division and therefore the impact of shared resources. While reaching quickly the impact of attentional division was restricted to ML the phase associated with the initial movement plan. Study two built on the findings from the first study to investigate if RT was truly independent of attentional effects by substituting fast reaching times with slow ones. The results of study two showed dual-task interference in both stages of the movement. This suggests resource sharing between the search and at least one factor involved in MT, possibly feedback and updating. The third and final study aimed to assess task parameter influences on movement production. The search task was manipulated by use of high and low difficulty (load) searches combined with either fast or slow movement speeds. When reaching slowly pre-movement planning time was longer, as was MT which reflected the area of experimental manipulation. Slow reaches were also more accurate than

fast reaching and more prone to the impact of target eccentricity. The eccentricity of the pointing target only significantly impacted performance while moving slowly coinciding with high accuracy. Fast reaching produces greater variability in performance possibly masking eccentricity effects. The manipulation of cognitive load impacted search performance as expected with high load conditions producing less accurate responses. While cognitive load had some impact upon goal-directed movement performance did not vary in a predictable pattern.

Overall attentional effects were evident throughout the reach, not only in ML and pre-movement planning time but also during the reaching stage. The impact of attention on RT was only observable during slow reaching. Although it may be inferred that attentional effects to RT in this experiment were mediated by online updating, this idea needs explicit testing in future studies. We also found that the parameters (and difficulty) of the tasks undertaken did impact goal-directed movement performance. Based on the difference in the patterns of effects when load was modulated via the cognitive (search load) compared to motor task (movement speed), it appears modifications to the motor element displayed more predictable load dependant effects. Overall, the pattern of results in this thesis demonstrate that dividing attention does have systematic effects on reaching performance and the predictable effects dependent on task load appear at this time to be modality specific.

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Heidi Dorothy Long

Acknowledgements

I would like to acknowledge and thank Associate Professor Anna Ma-Wyatt for all the work she put into developing me as a researcher. I am truly grateful for her limitless understanding and unfailing sense of humour and blessed to have her as a mentor and a friend. I would also like to thank Associate Professor Nick Burns for his advice and support throughout.

To my thesis support group Laura and Katie, I don't know how I would have made it without your support and stern lectures about finishing what you start. A big thank you to fellow first floor denizens for your valuable advice and helpfulness with data gathering, Adam, Dinis, Emma, Jess, Drew, Lauren and Steve, you guys made the experience as enjoyable as was possible ☺

I am extremely fortunate to have the most wonderful family who have supported me and helped where possible, I can't express how grateful I am! Particularly my daughters Starr and Ivy and Mum & Dad.

I would also like to thank all my friends for their understanding and faith in me. And finally thank you to Hamish, Mishka, Felix and Sabbath for the laughs and calming purrs.

List of figures

Abbreviations (in order of appearance)

Movement Latency – ML

Reach Time – RT

Lateral Geniculate Nucleus – LGN

Cortical Magnification Factor – CMF

Functional Magnetic Resonance Imaging – fMRI

Event Related Brain Potentials – EPR

Attentional Blink – AB

Posterior Parietal Cortex – PPC

Perceptual Load Theory – PLT

Perceptual Load – p-load

Liner Mixed Methods - LMM

1. Introduction

1.1. Goal-directed movements are the foundation of many tasks of daily living and provide valuable interaction with the surrounding environment. Although important, the influences, limitations and constraints on these movements are not fully understood due to their complex nature and the network of interacting underlying mechanisms employed in movement production.

Goal-directed movements are commonly used for human interaction and manipulation of the surrounding environment. Every reach, grasp, point and touch requires the use of a tightly controlled hand movement made to a specific location in space. Before a movement is made the target must be selected from the surrounding area. There is evidence that this process of selection relies on attention and some aspects of decision making to make the movement and achieve the goal. For the movement to be successful, the hand must be as close as possible to the target area at the end of the movement. For example, turning on lights requires enough accuracy to touch the switch which represents a relatively small area in the visual field. In other words, most visually guided movements that people make are goal directed and the consequences are based on the success or failure of the movement to achieve the desired outcome. The cognitive, visual and motor systems all contribute to goal-directed movement production forming a complicated network of underlying mechanisms.

The making of goal-directed movements requires information from more than a single sensory modality. As a consequence processing for movement execution must integrate information from differing sources into a single movement plan. One obvious source of sensory information used in goal-directed movement production is motor information. Proprioceptive information (unconscious spatial awareness of the body) provides sensory input about the position of the body before the initiation of the movement: the movement's starting position and the hands location in space. Additional sensory information provided by the proprioceptive system include the current muscle tension present in the arm before

moving and information from the muscles surrounding the eye that assists the calculation of gaze direction. Yet awareness of the body only provides part of the information needed, the visual system provides information about the environment and the movement's target location. In order for the central nervous system to achieve coordinated muscle contraction resulting in controlled movement, fine grained information from both visual sources (initial target position) and motor sources (initial hand position) are vital for movement planning (Desmurget, Pelisson, Rossetti & Prablanc, 1998; Sarlegna, Blouin, Bresciani, Bourdin, Vercher & Gauthier, 2013). The planning stage of a movement involves the use of both visual and proprioceptive information (Desmurget et al, 1998; Sarlegna et al, 2013) but while these signals interact, they do not necessarily combine (Balslev, Miall & Cole, 2007). These findings are consistent with the idea that visual and proprioceptive resources may be allocated in a flexible way. The assignment of weight (or relative importance) being managed in a task specific manner (Sarlegna, Blouin, Vercher, Bresciani, Bourdin & Gauthier, 2004). Because visual and proprioceptive information do not necessarily combine, the goal-directed movement system has to deal with two sources of information about the position of the body and the target, each with a different frame of reference. Cognitive functions assign relative weight to each source of information dependant on the task undertaken and environmental constraints (Sarlegna et al, 2013).

The allocation of attentional resources is an important aspect of goal-directed movement. It will be briefly discussed here, however as a central factor to this thesis, the concept of attention will be discussed in greater detail later in the literature review. The distribution of attentional resources decides which areas receive more cognitive processing than others As processing increases so does the level of perceptual detail available. Investigation into brain functioning and attention have found shifts in the areas of attentional enhancement are linked to selection of the target and subsequent increase of resources

deployed to that object (Forster & Eimer, 2007). The need for attentional processing boosts is due to the effects of neural noise which limits visual and motor performance. Neural noise refers to random fluctuations in a signal which is not integral to the signal and may be creating information distortion. Each system contributing to the movement brings an element of noise (or error) to the process. Goal-directed movements reflect a collaboration between motor, visual and cognitive systems each of which is necessary for movement production. Over the time course of a movement different sources of information may be more relevant to movement success than others. The complexity of the system means the exact parameters of the deployment of attention over the time course of a movement are still under investigation and are a primary focus of this thesis. The section that follows provides a more detailed look at visual system contributions to goal-directed movements and how they shaped the current investigations.

1.2. The goal-directed movement system makes use of visual information throughout the movement, it assists initial movement plan and online correction. Any experiment designed to study goal-directed movement needs to be aware of how the structure of the eye and visual processing impacts movement production.

Light enters the eye through the pupil hitting its inner surface (the retina). Photoreceptors in the retina detect fluctuations in light, perform the first stage of data processing then transfer the signals to the next retinal layer activating the ganglion cells. Ganglion axons merge and form the optic nerve which transports the signals away from the eye and into the cortical regions where even more detailed processing occurs. The optic tracts lead to the lateral geniculate nucleus (LGN), a region in the thalamus which projects information from the retina to the primary visual cortex in the occipital lobe. Local spatial representations are obtained by changes in the firing rate of cells attuned to specific stimuli.

The area of visual space where appearance of this stimuli induces a change in response from a cell is called its receptive field.

The retina is constructed of rods (which respond to luminance levels) and cones (which encode colour information), the density and frequency of this cellular arrangement is vital to visual system functioning (Hendrickson, Bumsted-O'Brien, Natoli, Ramamurthy, Possin & Provis, 2008). Therefore the physical structure of the eye constrains the quantity of information along with how it is received and processed. For instance greater photoreceptor densities gather more information about a specific spatial location. As there are larger quantities of data for this area of the visual field generally more cortex is devoted to its processing. The traditional visual field division is dichotomous and consists of central and peripheral vision. The area of high acuity corresponding to the fovea is commonly referred to as central vision and consists of only a small part of the visual field. Any part of the visual field that falls outside central vision is referred to as peripheral vision.

The retinal position corresponding to central vision has the highest density of photoreceptors and these cells have greater overlap of receptive fields than other retinal locations. This organisation increases the processing associated with this area of visual space and results in increased resolution. Resolution in the fovea is so great it is considered an area of hyperacuity with thresholds for position discrimination better than the width of a photoreceptor (Westheimer & McKee, 1977). Gaze fixation once the eyes have moved to the target may operate to facilitate directed movement by placing the target in an area of high visual acuity (Crawford, Medendrop & Marotta, 2004). As eye movements mean a change in the area that is being foveated. It makes intuitive sense then that saccades play an important role during inspection of a scene to select a goal for the movement. This supposition is supported by the landing positions of saccades and hand movements usually being spatially correlated (e.g. Neggers & Bekkering, 2001).

Central vision has a key role in the planning and guidance of goal-directed movements. Land, Mannie and Rusted (1999) used eye tracking conducted in a natural environment to investigate the relationship between the eye and the hand while engaged in a simple familiar task (making a cup of tea). They found that during goal-directed movements the eyes preceded the hands but the landing position of eye and the hand were tightly spatially correlated. As an indication of the importance of central vision to aimed movement, task irrelevant gaze fixations were reduced during movement production (Land, Mannie & Rusted, 1999) as central vision's increased processing capabilities deployed at fixation were reserved for task relevant objects.

In daily life eye and hand movements are usually tightly coupled (Land & Hayhoe, 2001): gaze shifts with movements of the eye, body, and head to fixate a movement target until the hand arrives (Lunenburger, Kutz & Hoffmann, 2000). This system of saccades moving the eye to the target before the hand allows for increased acuity of online visual feedback in the final stages of the movement trajectory giving increased resolution to base final corrections on (Lunenburger et al 2000). Eye movements do more than place stimuli on certain retinal positions, they also engage additional resources towards the target of the movement. Zirnsak, Steinmetz, Noudoost, Xu and Moore (2014) found when saccades were planned neurons involved in the prefrontal gaze control area processing the target location showed biased visual receptive field activation, this suggests simply planning a movement increases cognitive processing to that spatial location. Eye movements are particularly important if engaged in a task which needs the high spatial resolution associated with central vision, such as visual searches which require the integration of visual features. In such instances saccades are deployed to bring the target into central vision (Over, Hooge, Vlaskamp & Erkelens, 2007).

Eye movements are important factors for action as well as movement preparation. How accurately a hand movement can be performed has been found to suffer under conditions of gaze stability and when saccades are suppressed (Prablanc, Echallier, Komilis & Jeannerod (1), 1979; Neggers & Bekkering, 2001; Prado, Clavagnier, Otzenberger, Scheiber, Kennedy & Perenin, 2005; Wilmut, Wann & Brown, 2006). This pairing does not only facilitate hand movements, the benefits of moving the eyes to the goal location seem to improve saccade performance along with the reach (Lunenburger et al 2000). The relationship is not limited to performance measures as it has been suggested that eye and hand movement plans are reliant on the same visual information (Sailer, Eggert, Ditterich & Straube, 2000; Kowler & McKee, 1987) and possibly draw on the same attentional pool (Neggers & Bekkering, 2000; Song & Nakayama, 2006). Attention has been shown to be deployed at various stages in the eye movement system. Covert attention (attention decoupled from eye movements) is deployed to the target location during the preparation stage before movement onset (Deubel et al, 1998; Khan, Song & McPeek, 2011; Rolfs & Carrasco, 2012) and saccades deploy focal attention by bringing the target into focal vision (McPeek, Maljkovic & Nakayama, 1999). The strong relationship between attention and eye movements reflected in attentional deployment is the central theme to the pre-motor theory of attention, an influential theory describing ocular and attentional interactions.

The pre-motor theory of attention describes a potential mechanism which governs the interaction between motor preparation and spatial attention (Deubel & Schenider 1996; Smith & Schenk 2012). According to this theory, motor preparation and spatial attention use the same neural substrates, are functionally equivalent, and a shift in spatial attention can be elicited by planning a goal-directed movement. Pre-motor theory is often discussed in relation to eye movements. According to the pre-motor theory of attention, eye movements receive a privileged position when allocating spatial attention (Rizzolatti, Riggio & Sheliga

1994). Some recent results suggest that despite its common linkage to eye movements, pre-motor theory provides a basis for ideas regarding the relationship between goal-directed pointing movements and attention and possibly all three systems (motor, ocular and attentional) working together (Khan, Blangero, Rossetti, Salemme, Luaute, Deubel, Schneider, Laverdure, Rode, Boisson & Pisella 2009; Smith & Schenk 2012). Hoever is is often necessary to reach without overt movement of the eyes because the eyes can only be deployed to a single location at any given time. Therefore multitasking often employs covert attention to boost capabilities without moving fixation from a second task. For example, when driving awareness of pedestrians competes for focal attention with watching a busy road and secondary tasks such as changing a radio station can be achieved without disengaging fixation from the road.

Moving the eye to fixate on the target may grant that area of space attentional priority but there are many occasions where that strategy is unable to be employed (Carrasco, Ling & Read, 2004). So what happens to hand movements when circumstances preclude eye movements? Withholding a saccade results in decreased hand movement accuracy (Neggers & Bekkering, 2001; Prado et al, 2005; Wilmut, Wann & Brown, 2006). Similarly, when gaze is stabilised by fixating the target the movement endpoint is more accurate. Fixation to a non-target area also increases reaching error (Neggers & Bekkering, 2000; Wilmut, Wann, & Brown, 2006). It has been suggested that since movements made with the eyes freely moving are more accurate than fixed eye conditions, a large attentional resource load is needed to hold the eye in an unnaturally still position (Wilmut, Wann & Brown, 2006). When gaze cannot be redeployed to a movements target via overt eye movements, visual processing of the area can still be enhanced with the use of covert attention (Schall, 2004). When undertaking a single goal-directed movement task, the eye is deployed before the hand to the target area and attention is deployed before the eye allowing attentional facilitation at the

target area before eye movement initiation (Deubel & Schneider, 1996; 2003). However, if two tasks are undertaken simultaneously gaze fixation may need to be at a different spatial location than the reaches target. This suggests the central visual region is not unique in supplying information for movement and the peripheral region also plays a role.

There is evidence that peripheral vision provides information vital for goal-directed movement performance. One example of this being the availability of peripheral visual information increasing the directional accuracy of reaching and therefore the reaches success (Abahanini & Proteau, 1999). As the peripheral region covers the majority of visual space, initial target localisation information is often provided by peripheral information (Posner, 1980; Desmurget et al, 1998). The larger surface area of the retina dedicated to peripheral vision means it takes in a greater amount of the visual field, therefore it is likely some online updating of the movement is achieved with peripheral vision (Proteau, Boivin, Linossier & Abahnini, 2000; Sarlegra, et al., 2004). Although a link between deficits in peripheral reaching and deficits in peripheral online correction to the movement have been suggested, additional investigations are needed before a conclusion can be reached (Gaveau, Pisella, Priot, Fukui, Rossetti, Pelisson & Prablanc, 2014). Based on peripheral visual information affecting goal-directed movement and the impact of the withdrawal of peripheral vision having been found to be variable across peripheral vision, Abahini and Proteau (1999) identified the need for a less holistic approach to peripheral vision. They have suggested the central/peripheral division of the visual field is too simplified and the retina may contain more than two functional areas. This would mean the traditional central/peripheral division based on the physical properties of the retina are too simplified to adequately represent the functioning of the early visual systems. A spatial division based on function rather than photoreceptor organisation would create multiple regions, potentially resulting in greater explanatory power in terms of perceptual performance.

The physiological finding of changes in retinal composition (the retina's physical structure) were paralleled in psychophysics investigations which found a steady decrease in the performance of a discrimination task under fixed gaze conditions, this was attributed to a decrease in the quality of visual information with eccentricity (Anstis, 1974, 1998). The decreasing number of photoreceptors is directly linked to a reduced quantity of retinal receptive fields and less cortex devoted to the processing of information from that area of the visual field (cortical magnification factor, CMF) (Anstis, 1998). The decline in image resolution may not be impacted exclusively by photoreceptors as resolution decrease has been found to closely mirror the decline in retinal ganglion cells (Stephenson, Knapp & Braddick, 1991). While physically the retina is singular physical structure, the variety of cells in the retina produces different performance and cortical responses which makes them functionally quite independent. In an investigation on the cortical activation produced by attention deployed in the different visual regions, Roberts, Delicato, Herrero, Gieselmann and Thiele, (2007) concluded there was a fundamental difference in cortical mechanisms operating in central and peripheral vision. When a target is shown in the periphery a network of complex mechanisms enable the final movement. In support of this, fMRI studies have found deficits within visually guided hand movements specific to peripheral vision (such as optic ataxia), providing further support for differing biological substrates for foveal and peripheral vision (Clavagnier, Prado, Kennedy, & Perenin, 2007; Prado, et al., 2005). The impact of attention on event related brain potentials (ERPs) has also been found to vary with task and visual region. ERPs showed greater activation for moving (compared to stationary) stimuli an effect magnified by presentation in peripheral rather than central vision (Neville & Lawson, 1987).

A tightly coupled relationship between visual acuity and retinal eccentricity exists, visual acuity decreases as retinal eccentricity of the target increases (Anstis, 1974; 1998; Stephenson, Knapp & Braddick, 1991). Anstis (1998) found performance deficits based on

acuity information increased as distance from the fovea increased, and did so in a way consistent with the proportion of estimated cortical magnification factor (CMF). The cortical magnification factor inspired the creation of m-scaling or the rate at which a stimulus needed to be enlarged with eccentricity to achieve equal discrimination abilities across the visual field. Processes more complicated than target perception have also been found to be consistent with changes in CMF. For example, when conducting feature or conjunction searches, the application of m-scaling has been found to counteract eccentricity effects (Carrasco & Frieder, 1997) suggesting a purely biological basis for these effects. However, performance changes with eccentricity do not always show a linear decline as they would if CMF was the only factor impacting task performance. Visual adaptation to flicker shows a rate of change in performance much slower than m-scaling would predict (Anstis 1998) and the detection of targets in noise at a location eccentric to central fixation has been found to exhibit larger effects than might be expected from eccentricity alone (Verghese & McKee, 2004). M-scaling may also fail to explain complex tasks, it has been found that poorer perception of complex spatial patterns in the periphery is not adequately explained in terms of comparisons with central vision (Stephenson, Knapp & Braddick, 1991). Also, Ilanainen and Rovamo's (1992) study which investigated colour adaptation and stimuli size on grey/white perception found the desaturation threshold conformed to expectations based upon m-scaling when investigating blue colour adaptation but not when investigating green or red.

The visual information gathered by central and peripheral visual regions make important contributions to goal-directed movement enactment. The accuracy and precision of these movements have been found to depend on the initial visual information available (Ma-Wyatt & McKee, 2006; Wilmut, Wann & Brown, 2006). This may be because the visual system contributes to the pre-movement plan, the target is identified and localised based on visual information (Sarlegna, Blouin, Bresciani, Bourdin, Vercher & Gauthier, 2003). The

initial movement plan is not the only part of a reaching movement that makes use of visual information about the position of the target and the hand. Visual information is also used to update a movement online (Ma-Wyatt & McKee, 2007) and has been found to operate throughout the movement and not just in its final stage (Saunders & Knill, 2003; 2005).

Despite these differences, the two visual regions can affect each other. For example, peripheral processing capacity during a letter recognition task can be degraded in the presence of focal stimuli (Salvemini, Stewart, & Purcell, 1996). The differences found between central and peripheral vision have been hypothesized to be due to the different roles played by the visual regions (Neville & Lawson, 1987); central vision's increased resolution processing details and judging distance in fine detail, and peripheral vision's movement sensitivity indicating a primary function of new object identification and target selection. Some part of the changes in perceptual performance with eccentricity from the fovea could be due to attentional effects. How attention impacts information processing can depend upon visual field location. For example, processing of an attentionally dependant conjunction search has been found to be faster at peripheral and slower at central spatial locations (Carrasco, Giordano & McElree, 2006). Moreover, when identifying a target letter in a display, Juola, Bouwhius, Cooper and Warner (1991) found attentional effects depend upon distance from the central fixation point. This finding is the foundation of their suggestion that attention is distributed in rings around central vision. Search tasks are not the only tasks to reflect a relationship between spatial location and attention. When engaging in sequential movements attention is deployed in greater magnitudes to the target with greatest eccentricity from central vision (Baldauf & Deubel, 2008). The increased attentional resource deployed to the area of least acuity is consistent with Juola et al's (1991) postulation that attention is one of the mechanisms in place to counter decreases in visual acuity.

The constraints imposed by visual system functioning provide the basic foundation of the experimental premise and stimulus display used in this thesis. While visual sensitivity to a number of attributes generally decreases with increased eccentricity from the fovea, it is also apparent that this is not always the case and therefore application of m-scaling is not a universal reflection of performance. Perceptual performance is consistent with retinal changes but it is as yet unclear how attentional distribution is impacted. Both tasks (a central search task and a peripheral pointing task) used in this thesis, required responses to visual stimuli. The alphanumeric search task was presented at central vision allowing it to be processed in an area of high acuity. Pointing task targets were presented in the periphery and could appear at one of two eccentricities (4° or 8°) to allow for investigation into the impact of visual spatial placement and attentional dispersion.

1.3. *The deployment of attention can influence visual performance and helps explain why all tasks are not impacted in a pattern consistent with changes in photoreceptor density. Many types of attention are involved in making a goal-directed movement but the degree of shared or independent resources involved is yet to be fully investigated.*

The deployment of attention can influence visual performance and helps explain why not all tasks are impacted in a pattern consistent with photoreceptor density. The world has an almost unlimited amount of information but the brain has a limited processing capacity, this could result in an information processing problem were it not for attention. Attention can be conceptualised as sustained concentration on a specific stimulus, thought or activity (Coleman, 2003). The allocation of attention selectively enhances sensory processing by the deployment of extra processing resources (Desimone & Duncan, 1995; Reynolds & Chelazzi, 2004). However, attentional aid to processing information does not come without cost. Deployment of resources to one area is linked to other areas being under-attended (Carrasco,

2011; Ling & Carrasco, 2006). So what decides if a visual stimulus is selected to be a focus of attention? Attentional selection could be a bottom-up process in response to stimulus attributes such as luminance change or the sudden appearance of a stimulus (Franconeri, Hollingworth & Simons, 2005), or it could be in response to the task or goal and as such be driven by top-down processes. A 'pop out' stimulus has low attentional demands as it differs from surrounding stimuli in a basic and highly noticeable way (such as colour or orientation) that can be identified by specialised cells and do not require heavy processing. Pop out is therefore thought to be driven by this bottom up distinction. A visual search task has higher attentional demands as it needs to bind visual features for discrimination and this requires a higher level of processing. Endogenous attention can be characterised as driven by top-down selection and exogenous attention by bottom-up processes. Results from monkey physiology studies indicate these two types of attention are individual. Some aspects such as duration of deployment are different but as they have been observed to interact they seem to draw on the same capacity limited system (Busse, Katzner, Tillmann & Treue, 2008).

Attention is understood to operate via a neural gain mechanism (Carrasco et al, 2004; Ling & Carrasco, 2006) that acts at several levels of visual processing (Morrone, Denti & Spinelli, 2004). Gain mechanisms for visual attention increase perceptual contrast (Carrasco, Ling & Read, 2004) which is consistent with the idea that attention boosts stimulus contrast gain in the early visual cortex (Ling & Carrasco, 2006). Based on this tight coupling between gain mechanisms, contrast modulation and attention it has been suggested increasing contrast is equivalent to attentional deployment (Roberts et al, 2007). The result is the deployment of attention increases neural response in the cortex which decreases distorting neural noise thereby boosting stimulus contrast (Roberts et al, 2007).

The attentional function which boosts processing in some areas leaving others under processed (Ling & Carrasco, 2006; Carrasco, 2011) operates to maximise goal relevant

processing with limited resources. This deployment of extra resources to specific areas leaves some of the visual areas under processed and open to perceptual flaws. One example of this impacting attention is inattentional blindness. This describes an event when an observer fails to be aware of a salient visual object because it is incongruent with expectations or attention is deployed at another area of visual space (Kreitz, Furley & Memmert, 2016). Inattentional blindness effects are not impacted by proximity of the attended and non-attended objects (Simons & Chabris, 1999) and appear to depend on the duration of the object in visual space rather than object saliency (Kreitz, Furley & Memmert, 2016). As attentional deployment selects areas of increased processing, without focused attention large changes to the visual scene may not be noticed and this perceptual failure is called change blindness (Simons & Levin, 1997).

While inattentional and change blindness are both examples of how attention's spatial properties negatively impact perception, temporal based effects can also be found. Attentional blink (AB) occurs when a series of items are shown rapidly and sequentially. Perception of the first target negatively impacts reporting performance of a second target (Dux & Marois, 2009). In this case attentional deployment at a spatial location at a specific time spreads over time to a second target presented at the same location just after the first. How attention is flexibly deployed in response to top-down goals is in itself a complicated issue. Attentional resource allocation may depend on the type of task undertaken. For instance, Greenberg, Rosen, Cutrone and Behrmann (2015) found spatial and object based attention rely on individual mechanisms resulting in task dependant attentional prioritisation. Others have found a single attentional pool for all tasks dependant on visual attention (Deubel, Schneider & Paprotta, 1998; Pastukhov, Fischer & Braun, 2009).

Attention for target perception may impact pre-movement planning but what about the remainder of the reach? What types of attention are involved? Visual attention is an

umbrella term which encompasses a range of attentional processes which have been identified as sub-categories. Spatial and feature based attention differ in key ways; spatial attention is deployed to specific locations in visual space, feature based attention deploys to specific object attributes such as colour and orientation (Hayden & Gallant, 2005). Spatial attention is traditionally linked to top-down attentional deployment explained in terms of gain control and suppresses responses outside the area of attentional focus (Gilbert & Li, 2013). Object based attention as is guided by object structure and fluctuates in response to object properties rather than top-down goal driven priorities (Olson, 2001; Scholl, 2001). Along with spatial and feature based attention, object based attention is one of the three main types of attention as described by Carrasco (2011) in a review of the visual attention literature.

As suggested by the AB effect, attention has temporal in addition to spatial components, most often characterised as transient and sustained attention. Transient attention is a type of covert attention characterised by a brief (250ms) application of attention which is stimulus driven reflecting attentional capture (Carrasco, Ling & Read, 2004), while sustained attention describes the prolonged deployment of attention. The function of the two temporal attentions differs as does their impact on task performance in relation to task spatial location. Transient attention improves texture segmentation tasks in the periphery but degrades performance at central vision (Talgar & Carrasco, 2002; Carrasco, Loula & Ho 2006; Yeshurun & Carrasco, 1998; 2008). Conversely, sustained attention can improve texture segmentation at all eccentricities (Yeshurun, Montagna & Carrasco, 2008). So there are two temporal attentional measures, one for quick sampling of visual space (transient) and one tied to the target of a current goal (sustained).

When the eye moves towards a location, attention is allocated to the location (overt attention) but attentional deployment can also be achieved decoupled from eye movements (covert attention). Overt attention is related to central vision and bringing the target into this

area of increased processing, while covert attention is associated with peripheral visual (Bisley, 2011). Covert attention helps monitor the environment (which may later be used to program a movement) because it is deployed in parallel across the visual scene while overt attention is limited to serial deployment (Carrasco, 2011). Castiello (1999) has hypothesised that overt and covert attention share an interactive role in movement control. Covert attention was identified as providing the preliminary information necessary for trajectory formation. Then overt attention is engaged to provide secondary information and feedback about the final stages of the movement. Brain imaging investigations have shown covert attentional shifts and motor planning cortex activation are closely linked (Foster & Eimer, 2007). Moore (2006) reported that brain neuroimaging and single cell recording studies have found both shared and individual segments to the attentional networks assigned to overt and covert attention, suggesting some degree of independence of resources in addition to highlighting the complexity of attentional processes.

How attention is flexibly deployed in response to top-down goals is in itself a complicated issue. Attentional resource allocation may depend on the type of task undertaken. For instance, Greenberg et al (2015) found spatial and object based attention rely on individual mechanisms resulting in task dependant attentional prioritisation. Other researchers have found a single attentional pool for all tasks dependant on visual attention (Deubel et al 1998; Pastukhov et al 2009). Any of the types of attention mentioned could impact a facet of gaol-directed movement production. The lesson to be learned is that attention is flexibly allocated and different tasks may draw on the same attentional pool or operate independently.

Attention is believed to be vital for the visual selection of a target (Baldauf & Deubel, 2008) for goal-directed movements. Movement production is not just sensitive to the presence/absence of attentional resources but also to what type of resources are deployed.

Song and Nakayama's (2006) study of the duration and trajectories of goal-directed movements in relation to 'broad attention' which covered the entire visual field (and so is dominated by peripheral vision) and 'focal attention' (a mixture of focal and undivided attention), found that broadly distributed attention was insufficient, focal attention was needed to enact visually guided actions. Attention impacts movements in various ways, enhanced perception of the movement target enhancement occurs with attention (Deubel, Schneider & Paprotta, 1998) and movement trajectory is also susceptible to the impact of attention (Song & Nakayama, 2006).

In addition to facilitating a movement, attention has also been shown to aid the perception of targets in visual space. Visual discrimination performance improves when the target appeared at the location of an accompanying goal-directed movement's endpoint (Deubel, Schneider & Paprotta, 1998; Khan, Song & McPeek, 2011; Stewart & Ma-Wyatt, 2015). Juola et al's (1991) finding that attention is distributed in rings around the fovea and Baldauf and Deubel's (2008) study which found increased attentional deployment to the target farthest from the fovea during sequential movements taken together indicate a possible relationship between retinotopy and attention which prioritising the fovea. The validity of this central attentional bias needs to be investigated. Makela, Rovamo and Whitaker (1997) investigated attentional division and CMF with eccentricity and found the division of attention between tasks (a spatial interval discrimination and a displacement detection task) did not impact performance regardless of eccentricity. Because attentional effects were impacted by eccentricity in a task specific manner changes need to be made to the CMF in order for it to achieve constant performance across eccentricities.

Making a goal-directed movement does not always occur in isolation. There are often multiple goals for which planning occurs concurrently, such as reaching for a drink while continuing to read or watching television while eating. Therefore the division of attentional

resources needs to be considered in order to understand how the deployment of attention impacts goal-directed movements. The sharing of resources between two tasks of the same modality could be expected to draw on the same attentional pool as both trigger attention using the same basic information. Salvemini, Stewart and Purcell (1996) found peripheral letter recognition was negatively impacted by the presence of a visual object at central vision. However, Jonikaitis, Schubert and Deubel (2010) have argued that it is still unclear whether dividing attention between a cognitive and a motor task draws on a single attentional resource or if modality specific attentional resources exist.

The broader aim of this thesis is to investigate visually defined goal-directed pointing movements under dual-task conditions and how they are shaped by the parameters of the tasks being undertaken. In order to achieve this aim a new experimental design was constructed (and validated) which allowed for flexible application of experimental modifications to both primary tasks. It permits assessment of factors previously established to impact movements such as attentional deployment and the visual eccentricity of the pointing target. Dual-task trials consist of a central alphanumeric search task and a peripheral reach, the target of which could appear at four or eight degrees eccentricity. Each task component was also performed in isolation allowing for comparative analysis between single and dual-task conditions. The search task used in the experimental design constructed for this thesis employed a short gap (16ms) between letter presentations guided by the AB literature. Furthermore inaccurate response trials were assessed for disproportionate levels between trials showing sequential target letters and those that did not. No evidence for AB effects were found negating it as a possible distorting factor and justifying this aspect of the experimental design. The results of study one are reported in Chapter Three.

The basic premise of the ability to multitask depends on the ability of attentional resources to be divided between tasks but some tasks draw on resources that are wholly

independent and others have to share whatever resources are available. Attention is often studied with the use of an interference paradigm where the effect of one task is assessed in relation to performance on another. If performance of one task interferes with the other, then it is assumed the two tasks draw on the same resources. Using this paradigm, Morrone, Denti and Spinelli (2004) found there were separate attentional resources for luminance and colour contrast, indicating that attention could be segmented or stimuli specific. This was supported by Hayden and Gallant's (2005) finding that spatial and feature based attention relied on different recourses. Conversely other researchers have found visual attention to be a single resource (Deubel et al, 1998; Pastukhov et al, 2009). These conflicting findings could indicate that attentional resources differ dependant on the types of visual attention in a task specific manner. There have been many types of attention identified but whether they rely on completely separate resources, or the same resource divided and involving allocation and interaction, has yet to be fully resolved. The deployment of attention can impact successful movement completion but there are other factors such as the speed of the movement that can also significantly affect the outcome of the movement.

1.4. The speed at which a goal-directed movement is made dictates the duration the underlying mechanisms have to operate, creating restraints on movement production. This is suggestive of a solution to conflicting findings regarding the presence of an attentional component to online updating. Movement speed may distort attentional impact on updating by limiting its operational duration and slow reaching may produce different patterns of attentional activation.

Goal-directed movements can usefully be segmented into stages as different times or stages of the reach have different information processing requirements. For example the resources needed for the movement planning (or feed-forward processes) may be different than those required for the online updating of the movement (or the feedback system). In the early stage of the reach (the acceleration stage) the movement plan dominates movement

dimensions (such as velocity and trajectory). Later in the reach (the deceleration stage) the plan is subservient to the updating information which may provide information indicating correction to the original movement plan is necessary (e.g. Soechting & Lacquaniti 1981). The importance of the different types of information also fluctuate during the course of a reaching movement, hand/motor information being heavily weighted at the start of the reach and vision receiving greater weight (presumably to aid in online updating) towards its completion (Sarlegna et al. 2004). Nor is it only the target's visual properties that are important. Ma-Wyatt and McKee (2007) found restricted vision of the hand and the target reduced the precision of goal-directed movements indicating visual information about both the target and the hand is important to the updating system. The deployment of attention between tasks also depends on task parameters such as the speed needed to complete the movement, or the relative difficulty of the task. Goal-directed movements exhibit a trade-off between a movement's speed and accuracy (Fitts' law) the faster the movement, the less accurate the movement endpoint (Fitts & Perterson, 1964).

Fitts' index of difficulty is generally referred to as Fitts' law and conceptualised as the speed/accuracy trade-off. Fitts used a finger tapping experiment the results of which lead to his construction of a speed/accuracy trade-off formula. The formula suggests 'D' (distance) and 'W' (width) could be used to work out an index of difficulty 'ID' which impacts upon the time taken (given time pressure) to move a pointer to enact a goal-directed movement (Fitts, 1954; Guiard & Olafsdottir, 2011). Fitts' as a speed/accuracy relationship able to be manipulated or calculated as a function of the tasks index of difficulty has had some support in the literature. Support has been found in goal-directed movement studies such as Fitts' initial experiments (Fitts, 1954; Fitts & Peterson, 1964), studies that looked at moving targets (Chiu, Young, Hsu, Lin, Lin, Yang & Huang, 2011), and with differing visual conditions (Wu, Kwon & Kowler, 2010; Medina et al, 2009). There has also been some supporting

evidence in the eye movement literature from investigations of sequences of saccades (Wu, Kwon & Kowler, 2010; Abrams, Meyer & Kornblum, 1989).

However, while data from many experiments are consistent with predictions from Fitts' law, there are other more complex experiments for which it does not predict results. Zhai et al, (2004) suggested two layers of speed/accuracy trade-off working together with one having linear relationships and one which does not. A need for a more complex model has been illustrated by Elliott, Hansen, Mendoza and Tremblay's (2004) study which found the speed/accuracy trade-off was impacted by the cognitive variable of practice and strategy use. This indicates there is more at work than the initial model accounts for. There have also been suggestions that Fitts' does not work in 3D space (Guiard & Olafsdottir, 2011) and that it fails to be predictive with very low difficulty tasks (Beamish, Bhatti, MacKenzie & Wu, 2006). This suggests that Fitts' law is not universal and may need to expand to account for more complex task demands. There have also been complexities associated with the understanding of goal-directed movements and Fitts' law as different speed/accuracy associations have been found for ML and MT (Mohagheghi & Anson, 2002). Additional evidence for Fitts not being universal is provided by Chi and Lin (1997) who demonstrated a non-linear relationship between speed and accuracy for saccade amplitude. What part of the reach is impacted by the speed/accuracy trade-off is also still a matter of debate. Mohageghi and Anson (2002) found the movement time (MT) adhered to Fitts' law while the movement latency (the time between stimuli appearance and movement commencement, ML) did not, while the results of Juras, Simoka and Latash's (2009) study found it was ML that was consistent with Fitts' and not MT. This lack of consensus requires further investigation but it does strongly suggest flexibility of the movement system in response to differences to movement speed.

Movement speed impacts online updating; the more time there is for feedback, the more correction is possible (Saunders & Knill, 2003). Particularly as slow movement trajectories can then be assessed for error by both central and peripheral vision (Bedard & Proteau, 2004). The speed of the movement also impacts the approach taken to enacting goal-directed movements. Hanson, Glazebrook, Anson, Weeks and Elliott (2006) found more time was allocated to pre-movement planning when the observer knew the information available for updating (in this case vision of the hand) during the reach would be limited. The relative value of feedback fluctuates with reach parameters. While feedback can be used to increase endpoint accuracy, it may be of limited use when engaging in fast movements (Gordon, Ghilardi & Ghez, 1994). Fast reaching limits the time available to gather updating information approximately 150ms is needed for the online updating system to process the relevant information, amend the original movement plan and start to adjust the movement (Ma-Wyatt & McKee, 2007). The impact of attention may not be stable across feedforward and feedback processes. When producing fast movements attention has been found to impact the movement latency (ML) (which incorporates movement planning time) but not reach time (RT) (which has an updating component) (Liu, Chua & Enns, 2008). It is as yet unclear if the differing impact of attention on the separate movement phases are a reflection of the differing properties of feedforward and feedback processes or if the reach is just too fast for updating to be engaged sufficiently for attentional manipulations to have a measurable impact upon goal-directed movement outcomes.

Updating and movement correction can occur without conscious awareness (Saunders & Knill, 2003; Gaveau et al. 2014) and as such may be an automatic, pre-attentive response which remains unaffected by experimental manipulations to attention. Sarlegna and Mutha (2014) found that a cognitively demanding task undertaken while pointing did not impact updating and movement correction which is consistent with updating being pre-attentive.

However suppression of an online correction has been found to be cognitively demanding (McIntosh, Mulroue & Brockmole, 2010) supporting the idea that updating has a cognitive component. It is also possible that updating and correction to goal-directed movements that appear unconscious may still tap a low level attentional resource (Gaveau et al., 2014). Gaveau et al. (2014) reported that observers with PPC lesions had deficits in conscious correction to goal-directed movements and normal subjects were unable to inhibit unconscious corrective movement to small movements of a target. The authors concluded both conscious and unconscious goal-directed movement corrections relied on similar flexible processes. These discrepancies regarding the role of attention for online updating highlight the need for further investigation into this area.

The second study was conducted to investigate if reducing reaching speed impacted the pattern of attentional distribution. While the first study utilised fast reaching, in the second study the reach task was manipulated by having slow movement speeds. This allowed for the comparison of attentional deployment under differing temporal constraints and evaluation of attentional distribution under different temporal demands. With ample time to function any impact of condition on the updating system should become apparent, effects that may be obscured with fast reaching movements.

It is not unusual for studies to require participants to make fast movements. During fast movements there is limited time for updating and it has been demonstrated that initial visual information associated with planning the movement can therefore have a greater impact on the movement outcome (Ma-Wyatt & McKee, 2006). These slower movements also offer an opportunity to measure the effect of experimental manipulations like dividing attention on this process of online integration of visual information. Fast reaches have been found to have a less flexible approach to movement enactment than those without time restraints (Hanson etal, 2006). The speed of a movement has a direct impact on how

successful a pointing movement can be, partly attributable to the processes captured by Fitts' Law and also because of the time for visual and proprioceptive feedback. The availability of feedback has been reported to increase movement accuracy (Gordon, Ghilardi & Ghez, 1994), because slower movements increase time available for online updating and movement correction (Saunders & Knill, 2003). Slow movements should provide conditions where experimental effects on feedback may be reflected in fluctuations in movement accuracy. So it seems the slower the goal-directed movement, the greater the ability to update and potentially the more accurate the endpoint. Due to the importance of updating it will be instructive to know if deployment of attention away from the movement limits updating capacities.

1.5. We can conceivably expect cognitive load to impact the making of goal-directed movements based on studies of similar processes (cognitive load and a motor task), but there is no direct evidence as yet. Load has been found to effect other motor tasks such as eye movements and walking so an investigation evaluating if this pattern includes reaching movements would be of benefit to the area of research.

The term 'Load' conceptualises how much of a resource a task uses given that the resource is limited (Lavie & Tsal, 1994). Cognitive load is an umbrella term used to explain the load associated with all the cognitive (processing) resources available to an individual. Memory, perceptual and attentional load are all parts of this cognitive resource pool (Lavie, 2005). Key to understanding how load is thought about is the idea that processing resources have a maximum capacity which limits perception, brain activation and behavioural outcomes (Lavie & Tsal, 1994). As cognitive complexity increases, task performance decreases (Plainis, Murray & Chauhan, 2001). Traditionally experimental designs utilising response to a target embedded in distractors have been used to investigate PLT (Lavie, 2005). Processing of distractors declines with increasing p-load of the primary task as it harnesses

most of the processing resources available. When task load is low distractors (task irrelevant stimuli) receive greater amounts of processing (Lavie, 2005). Increasing the number of objects in the array (set size) reliably increases p-load decreasing the processing of distractors (Lavie, 1995; Lavie, Beck & Konstantinou, 2014). Decreases in p-load can be obtained by reducing set size or increasing the similarity between target and distractors (Stolte, Bahrami & Lavie, 2014). This relationship is not unidirectional as the visual information of the target is degraded the associated cognitive load of the task increases (Yu, Prasad, Mir, Thakor & Al-Nashash, 2015). Cognitive load has been found to impact more than basic visual tasks, the interference produced by distractors is evident even with visually rich stimuli such as faces and environmental scenes (Minamoto, Shipstead, Osaka & Engle, 2015). Attention has been found to enhance visual perception and increases neural response in the visual cortex to a target stimulus (Pastukhov & Braun, 2007) and basic visual functions, such as contrast discrimination, have shown improvement with attention (Morrone, Denti & Spinelli, 2002).

More contentious is how much information is processed before attention is deployed (pre-attentive processing) which has given rise to a series of postulations known as the early-selection/late-selection debate. The early selection theory, suggest that only enough to assess what needs to be attended to gets processed preattentively. In the early selection view attention filters information at an early stage in processing stream (Broadbent, 1954). The late selection theory supports the idea that sensory signals all receive a significant amount of processing with attention adding direction later. In the late selection view attention filters unwanted stimuli at a late stage in processing, failure to notice events are a memory not a perceptual failure (Deutsch and Deutsch, 1964). Others again (Treisman, 1964, Attenuation theory) suggest a mid-selection process with some input from all signals being processed but the ones without attention directed towards them are tuned down. The perceptual load (PLT) theory (Lavie, 1994) accounts for the differences in the results on which these differing

theories are based by introducing a flexible contingency (perceptual load, p-load) which allows early or late attentional selection based on the level task difficulty.

PLT looks at the role of attention in information processing. PLT suggests perception has a limited capacity but that it operates automatically in an involuntary manner (so it processes all it can within its capacity). The key assumptions of PLT are that processing continues until capacity is reached, voluntary (top-down) control is limited to task prioritisation (setting the goal) and task load impacts information processing. PLT explains the early/late selection debate in terms of associated task load. When p-load is high there are large amounts of information to be processed, consequently capacity is reached processing the stimuli attended to voluntarily (under top-down, goal driven allocation) reducing the processing (and perception) of information not deliberately attended to, this results in early selection. Low p-load results in late selection, since perception cannot be voluntarily stopped while there is still capacity available to be deployed both attended (goal relevant) and unattended (goal irrelevant) stimuli will be processed (for reviews see Lavie, 1995; Lavie, 2005; Lavie, Beck and Konstantinou, 2014). PLT applies a kind of mixed models approach, in that it suggests attentional filtering is flexibly applied depending on the p-load of the task undertaken. When the central task has high-load it employs the majority of the processing resources leaving little for peripheral processing resulting in deficits in peripheral perception. Under low-load conditions more resources are allocated to peripheral processing increasing peripheral distractor interference. An understanding of p-load and its impact on processing may be key to understanding our perception of the world around us. In their 2014 review, Lavie, Beck and Konstantinou concluded that p-load is important for perceptual awareness, from basic contrast detection to high level semantic content. The effect of p-load has been found to be robust, it continues to be observed even in instances when the distractors are expected and there is top-down instruction to ignore them (Lavie, Beck & Konstantinou

2014). While it is generally agreed that p-load is reflecting some real cognitive process, the underlying mechanisms still a matter of debate and not all theories of attention and perception conform to PLT parameters.

There have been suggestions that the effects of perceptual load (p-load) may be at least in partly attributable to dilution effects caused by the experimental design used in many studies of p-load. Dilution theory is the predominant alternate theory to PLT, it was suggested by Benoni and Tsal (2010; 2013) and based on concerns about the methodology classically used to measure p-load, low-load displays having only one stimulus that could appear at several different locations, and high-load displays presented the target imbedded in distractors. It has been suggested that the presence of additional stimuli may cause dilution effects in the high-load conditions (Benoni & Tsal, 2013). Thus the single stimulus acts as a pop-out display harnessing all the available attention and therefore processing resources. This is fundamentally different to the high-load display that is a search task and so resources must be allocated to more than one position diluting the amount of resources allocated to processing the target stimuli. Although a fairly new area of research support so far is promising for dilution theory. In their 2010 paper Benoni and Tsal concluded that it was dilution (the absence/presence of neutral items) rather than p-load that is the factor causing p-load effects, however, in their 2012 study they concluded that p-load and dilution were both facets of task difficulty. Nor is Dilution Theory alone, other theories such as the Theory of Visual Attention (TVA; Bundesen, 1990; Kyllingsbaek, Sy & Gresbrecht, 2014) and Visual Excitability Theory (VET; Carmel, Thorne, Rees & Lavie, 2011) both suggest modifications to the PLT model. The studies contained in this thesis do not directly test the current load theories, the purpose of investigating them was to ensure the stimuli used conformed to current understandings about load manipulation.

Although there have been some investigations into load impact on nonvisual modalities, the vast majority refer to awareness of visual elements in space or the perception of visual stimuli. This highlights the central role of vision in load research. The position of the target in space in relation to central vision, or target eccentricity is also of primary importance not least because of it prominence in many of the experimental designs used to study the impacts of task load (eg search task, flanker tasks and RSVP). We can expect the spatial location of the task to impact performance based on several areas of converging evidence. Past findings suggest preferential allocation of attention to central vision when a stimulus is presented there (Wolfe, O'Neill & Bennett, 1998; Mackeben, 1999; Beck and Lavie, 2005; Handy, Soltani & Mangun, 2001), which is consistent with attentional load at fixation reducing cortical activation in areas associated with peripheral processing (Handy, Soltani & Mangun, 2001; Schwartz, Vuilleumier, Hutton, Maravita, Dolan & Driver, 2005). These findings suggest the central/peripheral division of space is a suitable conceptualisation and an area of interest regarding studies of load. The use of a dual-task, interference paradigm is commonly used in studies of both attention and load. This paradigm is based on the principle of resource sharing; if dual-task conditions produce worse task performance than single-task conditions the conclusion that they share resources is reached. Utilising a dual-task paradigm detrition of recognition performance (Landolt rings test) with eccentricity has been found and this detrition was more pronounced under dual-task conditions (Bondarko, Danilova, Solnushkin & Chikhman, 2014). Studies have found high-load tasks at central vision to illicit worse peripheral performance than under low-load conditions (Chan & Courtney, 1993; Carmel, Saker, Rees & Lavie, 2007). Nor is the peripheral task the only one impacted by dual-task conditions, studies have also shown degradation of performance for the central task as well (Chan and Courtney, 1993; Plainis, Murray & Chauhan, 2001; Pastukhov, Fischer & Braun, 2009).

1.6. Summary and Aims of the thesis

Many times every day we use goal-directed movements to interact with our environment. Goal-directed movements rely on visual information throughout their performance duration. The visual system provides information about the target's initial location in space, its spatial stability and provides feedback allowing for online updating of the movement. Attention is important to the sensorimotor system and the flexible distribution of attention over the visual scene can impact movement making. Fluctuations of attentional resources are inevitable as deployment to one location (increasing its processing) is accompanied by reduced processing of other areas. People often perform more than one task at a time requiring a division of attention between goals if both tasks draw on the same resource pool. How attention is deployed during reaching depends on factors such as the speed of the movement and possibly how difficult the task is to complete. Movement speed also constrains the updating system as the faster the reach is the less time available for the processing of feedback and online correction to the movement.

The overarching aim of this thesis is to investigate the parameters that determine how a goal-directed movement is performed and to assess how changes in these parameters impact task performance. The studies in this thesis employ a dual-task paradigm consisting of a central search task and a peripheral goal-directed pointing movement. These tasks were used to investigate how experimental manipulations of attention and the difficulty of aspects of the movements altered performance of simple goal directed movements. In study one an investigation into whether dual-task performance of a cognitive and motor task reflects attentional division and so shared resources. Measures of performance included search response, reach endpoints and movement time measures assessing if these factors draw on a shared attentional pool or if some aspects of performance are functionally independent. In study two a manipulation of the movement task was achieved by employing slow movement

speeds allowing investigation into how the different movement speeds impact upon patterns of performance. The manipulation of reaching speed allows assessment of how updating is associated with attention. In the third study the search task was manipulated to reflect high and low load conditions, this aimed to explore the impact of cognitive load while reaching. This is a new area of investigation and the objective was to consider how different levels of cognitive-load impact overall task load and how that impacts performance.

2. Preface to Paper 1

How well a goal-directed movement is aimed and performed is dependent on how well the task is attended to, which mediates the allocation of processing resources. There is considerable evidence that attention is a fluid resource that can be divided between tasks. Attention is integral to the goal-directed movement system, this study focuses on visual attention. Visual information is used to localise and update goal-directed movement and attention can modulate the amount and quality of this information (Desimone & Duncan, 1995; Reynolds & Chelazzi, 2004; Roberts et.al 2007). How information is collected is dependent on the physical characteristics of the retina (Anstis, 1996) and deployment of attention across the visual scene.

This study continued the traditional use of a dual-task experimental design for testing attentional effects. All tasks were performed alone to provide an undivided attentional baseline for task performance. This gave us the ability to assess performance differences under conditions of focused and divided attention. This was achieved by the application of an interference paradigm which had the overall goal of assessing if there was a shared attentional component between a central cognitive task and a goal-directed movement to peripheral vision. As there were two possible eccentricities at which the pointing target could appear in order for the impact of visuospatial placement and attentional dispersion to be investigated.

This study had two major tasks to achieve in terms of the overall goals of the thesis. The original experimental design needed to be validated and an assessment of the shared or individual nature of the attentional resources being applied to the scene was needed. Additionally it directly relates to the aims of this thesis by assessment of how goal-directed movement components were impacted by attentional deployment at central vision when reaching quickly.

Statement of Authorship

Title of Paper	The distribution of spatial attention changes with task demands during goal directed reaching
Publication Status	☑ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Long, H. and Ma-Wyatt, A (2014): The distribution of spatial attention changes with task demands during goal directed reaching *Experimental Brain Research* 232(6) 1883-1893

Principal Author

Name of Principal Author (Candidate)	Heidi Long
Contribution to the Paper	Devised experiments, ran experiments, analysed data, writing and editing.
Overall percentage (%)	
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.
Signature		Date	

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i.   the candidate's stated contribution to the publication is accurate (as detailed above);

ii.   permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Anna Ma-Wyatt
Contribution to the Paper	Devised experiments, assisted in analysis and writing.
Signature		Date	1/3/17

Name of Co-Author	
Contribution to the Paper	
Signature		Date	1/3/17

Please cut and paste additional co-author panels here as required

3. Paper One

The Distribution of Spatial Attention Changes with Task Demands during Goal-Directed Reaching

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Words: 6775

Figures: 6

Keywords: goal-directed movement, divided attention, eccentricity, dual task, spatial attention

3.1. Abstract

Goal directed movements are commonly used to allow humans to interact with their environment. When making a goal directed movement in a natural environment, there are many competing stimuli. It is therefore important to understand how goal directed movements are affected by divided attention. We used a dual-task paradigm to investigate the resource sharing between a search task in central vision and a peripheral motor pointing task completed concurrently. Results suggest some degree of shared attentional resources between these two tasks with both central and peripheral tasks having performance degraded under dual-task conditions. As movement latency but not movement time was affected by dual-task conditions, it seems that there is a cost to reach performance if attention is engaged away from the movement goal. Interestingly, this cost is associated with movement planning rather than execution.

3.2. Introduction

People use goal-directed movements to interact with and manipulate objects in their environment. Since goal-directed movements are typically made to visual targets, it makes intuitive sense that visual information plays a key role in the planning and execution of these movements (e.g. Ma-Wyatt and McKee 2006, 2007; Wilmut et al. 2006). Attention can be allocated to the goal of the movement (Baldauf et al. 2006) and some even argue that attention is necessarily deployed with every movement (Castiello 1999; Bekkering and Pratt 2004). As goal-directed movements and attention have a close relationship, it is important to understand how the two different systems interact and affect each other and how divided attention affects the performance of goal-directed movements. Attention can be divided — the idea of multitasking rests on this premise. However, it is unclear whether dividing attention between a cognitive and a motor task draws on a single attentional resource, or whether modality-specific attentional resources exist (Jonikaitis et al. 2010). Song and Nakayama (2006) investigated how the deployment of 'broad attention' (which covered the entire visual field and is dominated by peripheral vision) and 'focal attention' (attention focused upon a single stimulus) affects goal-directed movements. They reported that focal attention was necessary to carry out visually guided actions. This idea that attention is required for the execution of a goal-directed movement is also supported by Deubel et al. (1998) finding that visual processing at the goal location is selectively enhanced by attention. If attention does enhance processing at the goal of the reach, the deployment of attention could also affect pointing precision and accuracy and so the success of the goal-directed movement.

There also appears to be a relationship between attention and retinal eccentricity but the dynamics of this relationship are complex. In view of past results that found performance

reduction (Anstis 1996) and acuity reduction (Anstis 1998) with greater eccentricities, it could be expected that the performance of goal-directed movement would be detrimentally affected by targets further from central vision. However, this is by no means certain, since attentional effects have been reported to be dependent upon distance from the central fixation point (Baldauf and Deubel 2008; Juola et al. 1991; McKela et al. 1997). Juola et al. (1991) suggested that attention may even be a mechanism that reduces the impact of eccentricity.

The decrease in visual perception with greater retinal eccentricity fails to be an adequate predictor of visual performance. For instance, although discrimination tasks conform to m-scaling linear decline, which correlates to the decline in photoreceptors in the retina (Anstis 1996), other tasks, for example adaption to flicker, show a rate of change in performance much slower than m-scaling would predict (Anstis 1998).

Why might attention be deployed differentially across the visual field? There are noted differences between the processing of visual information in the fovea and the periphery, above what could be expected from photoreceptor density alone (Stephenson et al. 1991). In an investigation on the cortical activation produced by attention at a neuronal level, attention was deployed towards or away from a neurons classic receptive field and it was found that attention enhanced the neuronal response by reducing external noise. Neurons associated with central vision were found to exhibit reduced spatial integration, while those associated with peripheral vision increased spatial integration by increasing the neuron's summation area (Roberts et al. 2007). Based on these findings, it was concluded that there was a fundamental difference in cortical mechanisms operating in central and peripheral vision.

Past studies have found that a task in central vision degrades the performance on a peripheral task. This outcome has been commonly explained as the product of divided

attention (Webster and Haslerud 1964; Leibowitz and Appelle 1969; Ikeda and Takeuchi 1975). In this study, we used a dual-task paradigm to explore the relationship between two tasks, one processed in central vision (an alphanumeric search task) and one in the periphery (a goal-directed pointing movement). Since both spatial localisation and alphanumeric search tasks have been found to require attention, so dual-task/divided attention conditions should show impaired performance if the two tasks draw on the same attentional resource. If, however, the tasks draw on different attentional resources, there would be no interference produced by doing the two tasks at once and performance in dual-task conditions would be no worse than in single-task baseline conditions. There is also a third possibility that of dual-task facilitation. There have been findings of dual-task facilitation (Balslev et al. 2007; Liu et al. 2008; Enns and Liu, 2009) or a task being performed better when undertaken with a secondary task than when it is performed by itself. Liu et al. (2008) reported dual-task facilitation to both the movement time (MT) and precision of a pointing movement when compared against single-task baseline conditions. Another instance of dual-task facilitation was observed by Spataro et al. (2013) in an investigation into memory encoding when a word presented at the same time or directly after an infrequent target presentation was remembered at a higher rate than baseline performance. These findings point towards the pre-deployment of attention to the visual scene producing an attentional boost to stimulus encoding.

The pre-motor theory of attention describes a potential mechanism governing the interaction between motor preparation and spatial attention (Smith and Schenk, 2012). According to this theory, motor preparation and spatial attention use the same neural substrates. They are functionally equivalent (in that they both deploy processing resources towards a spatial location), and a shift in spatial attention can be elicited by planning a goal-directed movement. Within this theoretical framework, eye movements receive a privileged position when allocating spatial attention (Rizzolatti et al. 1994). Some recent results suggest

that despite originally being a theory related only to eye movements, the pre-motor theory of attention might also be a useful framework for investigating the mechanisms underlying goal-directed movements (Smith and Schenk 2012; Khan et al. 2009). This is perhaps not surprising given that goal-directed movements are typically accompanied by an eye movement.

The effects of attention on goal-directed movement performance are often studied with the use of an interference paradigm. In an interference paradigm, the effect of one task is assessed in relation to performance on another. If the performance of one task interferes with the other, then it is assumed the two tasks draw on the same resources and performance. Hayden and Gallant (2005) used the recordings from a single neuron in V4 under differing attentional conditions to demonstrate that stronger attentional activation occurred later in the visual response for spatial attention and at a constant level throughout for feature-based attention. Hayden and Gallant argued that these results meant spatial and feature-based attention relied on different resources. Deubel et al. (1998) used a dual-task paradigm to investigate the division between ventral and dorsal processing in primates. They found discrimination of a target was best when it was coupled with a manual aiming movement, suggesting that the attention deployed in conjunction with a manual movement also aided the target discrimination task. Pastukhov et al. (2009) used attention operating characteristics during visual discrimination to establish that visual attention may be a single resource. Studies that have used interference paradigms to investigate the aspects of visual attention have resulted in conflicting findings that could indicate that attentional resources differ depending on the types of visual attention required to execute a task. If this is the case, a cognitive based search task and a manual pointing task could rely upon different attentional pools despite both being present in the same visual field.

Movement planning and the transport of the hand have been identified as discrete stages of goal-directed movements. Costs specific to movement planning have been measured in terms of changes to the time between stimulus onset and movement onset (referred to as movement latency, ML) (Liu et al. 2008; Barthelemy and Boulinguez 2001). The movement time (MT) or the time between the start and the finish of the reach can also be decomposed into two periods, an acceleration stage towards peak velocity and then deceleration towards the movement endpoint (Soechting and Lacquaniti, 1981). While the initial phase of the reach is thought to rely heavily on information available during the planning stage, the period of deceleration benefits from the incorporation of online feedback into the movement plan. Given these differences in the information used in different phases of the movement, it is therefore important to understand how the deployment of attention away from the goal of the movement at these different times affects overall movement outcomes.

In the present study, we asked observers to reach quickly to limit the time for online updating. Studies of goal-directed movement and attention, using a dual-task paradigm involving a perceptual and a motor task, have not yet formed a consensus about whether attentional load impacts both the planning and execution of a movement (Hesse et al. 2012) or whether the impact is restricted to the planning stage (Liu et al. 2008). We kept the basic task demands constant across three conditions (in that all required a goal-directed movement) and varied the demands of the task by asking participants to point without the concurrent task (baseline performance), point with the search task cessation during movement planning (part reach condition), or with the continuation of the search task throughout the reach (whole reach). We investigated how attention can be deployed during a movement by manipulating the time into the reach that the dual task concluded.

In summary, the first hypothesis predicted that a dual-task cost would be evident between a central search task and a peripheral goal-directed pointing movement. Secondly, an

investigation relating to eccentricity, attention and goal-directed movements will be undertaken with the expectation that increased eccentricity will result in decreased task performance. And finally, the impact of disruption to the central search task (by cessation during pre-movement planning) compared to the continuation of the dual-task conditions throughout the reach will be assessed for both task outcomes.

3.3. Method

3.3.1. Participants

Four observers (N = 4) aged from 23 to 38 years participated in all stages of the experiment. As typical with psychophysics experimental design, statistical power was provided by large numbers of trials rather than a large sample size. All four observers were experienced psychophysical observers who were naive to the purposes of the experiment. All participants were right-hand dominant as assessed with the Edinburgh Handedness Inventory and so responded to the stimuli with their right hand. Participants had normal or corrected to normal vision and unimpaired arm movement ensuring that the data represent normal visual and motor responses. Informed consent was obtained in accordance with the guidelines and reviewed by the human ethics committee of Adelaide University. All participants were free to withdraw consent at any time in the study, and feedback was offered on completion of the study.

3.3.2. Materials

The experiment was presented on a computer monitor with a 17″ ElO touch screen with a resolution of 1,024 × 768 pixels and a screen refresh rate of 60 hz. The touch screen was comprised of a normal CRT overlaid with a pressure sensitive layer that enabled the time and exact location of a point to be recorded. Stimuli were presented in eight target positions that appeared 90° apart (at points consistent with twelve, three, six and nine o'clock on a clockface) and at two eccentricities, 8° and 4°, from the central fixation point, this resulted in a difference of 12.6° and 6.3°, respectively, along the circumference (see Fig. 1).
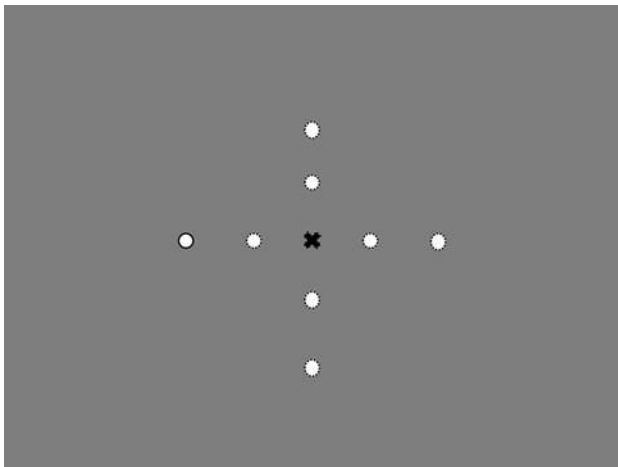
Fig. 1. Onscreen position of possible stimuli appearance points

The pointing target stimulus was a high-contrast white dot (43 % Michelson contrast), 0.5° in diameter and was presented for 100 ms. A computer keyboard was used to indicate search task answer. A stable 40 cm distance from face to screen was achieved with the use of a chin rest; the mouse was positioned 40 cm from the centre of the computer monitor at a 20° angle towards the right-hand side as all participants are right-hand dominant. Stable viewing conditions and luminance levels were ensured by regular monitor calibration using a Konica Minolta Chroma metre cs-100a.

Experiments were conducted using custom written software in Matlab using the Psychophysics toolbox (Brainard 1997; Pelli 1997). The outcome measures recorded were the location on the screen at which the pointing target was presented, and the location of the touch response, along with the time between stimulus presentation and movement commencement (ML) and the duration of the movement in milliseconds (MT). The number of target letters presented and the observers response to how many target letters were seen was also recorded for the analysis. Data were analysed offline using SPSS and Matlab.

3.3.3. Procedure

The experiment was conducted in a quiet, semi-dark room (the only light was generated by the computer monitor in use) to minimise light from external sources that could influence the luminance received from the computer screen. Luminance has previously been identified as a property that 'captures' attention (Franconeri et al. 2005), suggesting the stimulus would harness the full load of peripheral attention available. The brief presentation time of the target (100 ms) ensured that localisation was conducted using peripheral vision and prevented attentional shifts (Deubel et al. 1998) that would benefit the movement. The quiet, dark conditions also reduced the chances of accidental attentional shifts and limited external sources of noise that could have competed with task requirements. The circular pattern of possible target positions around a central fixation point (as used previously by Ma-Wyatt and McKee 2006, 2007; Song et al. 2007) was used to prevent response bias and left/right bias. Juola et al. (1991) investigated the deployment of attention across the visual field utilising an alphanumeric search task and cues (or no cues) to manipulate attention. They found attentional benefits when searching for targets of a similar size to the cue. Their results indicated that attention was deployed to a ring-shaped area and search task

performance within the ring showed benefits compared to outside the ring. By having stimuli in a circular array for both eccentricities, the pointing stimuli conformed to this structure ensured no confounding elements would be apparent in the eccentricity data due to the task covering too great a portion of the visual field.

3.3.4. General conditions

Participants were seated in a chair adjusted to their individual height for comfort and placed their chin on a chin rest, which ensured a 40 cm distance between the eye and the computer screen. They were instructed to wait until a dark central fixation dot appeared in the centre of the screen that represented the programs readiness to begin the individual trial. The participant's readiness to begin each trial was indicated by pressing the right-hand side key of the computer mouse that was situated 40 cm from the centre of the screen. They were instructed to do this using their right index finger and to respond to the pointing stimulus with the same digit. Participants received instructions then a set of practice trials (practice trials encompassed a trial for each of the eight possible target locations) before commencement of data collection for each of the experimental conditions. This made sure the instructions were correctly comprehended and the participants were comfortable with the procedure guarding against any interference produced by task uncertainty. Each participant was offered extra practice trials if so desired. Experimental and baseline conditions were presented in an individually randomised order for each participant. Conditions were counterbalanced across participants to negate any practice or order effects.

3.3.5. Conditions

The study was a repeated measures design with each observer participating in each element of the experimental procedure that provided their own baseline. The first experiment consisted of three baseline conditions, which enabled comparative analysis against the performance of the combined tasks in the two experimental conditions. The experimental process took two and a half to 3h to complete, which raised the possibility of visual and muscle fatigue along with the probability of attentional lapses that could compromise findings. To avoid these potential confounds, participants completed the experiment in multiple sessions over several days. A single testing session lasted 30 min to 1h at a time. Observers were also offered a break from testing between blocks.

The three baseline conditions provided data on individual aspects of the experimental conditions, which could be used for comparative purposes. Two sets of trials collected baseline data for the letter search task. In these tasks, an initial grey screen with fixation point in the centre of the screen was shown. The observer indicated readiness to begin the trial by pressing the right-hand side mouse key. A string of letters (from 'A' to 'J') was then presented serially in the centre of the grey screen. Each letter was presented for 16 ms with a 4ms gap between letter presentations to eradicate backward masking effects. After completion of the letter string the question 'how many times did you see 'H'? appeared and the trial was completed after the observer responded to the question using the number array on the keyboard.

The letters were displayed one at a time as visual search has been found to be processed serially (Wolfe 2003). In a pilot study of this experiment, the number of letters presented was found to influence the percentage of correct responses. Each baseline letter task was therefore constructed to match the number of letters presented in each of the

experimental conditions. The final baseline condition was solely concerned with the pointing involved in the experiment and is a single undivided attention task.

After the observer indicated readiness to begin (by pressing the right-hand mouse key and keeping it depressed until pointing with the same finger) at which stage the central fixation dot disappeared and a pointing target was presented (a spot with a high luminance contrast to the background), pointing targets could appear at one of eight possible location displayed at two eccentricities (see Fig. 2).
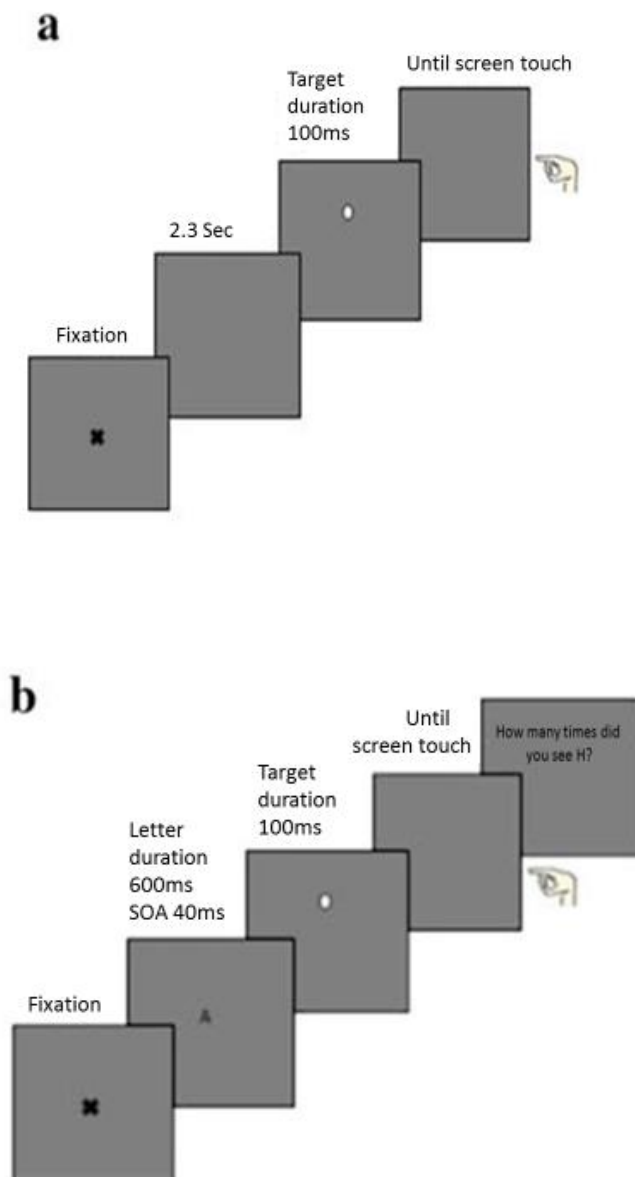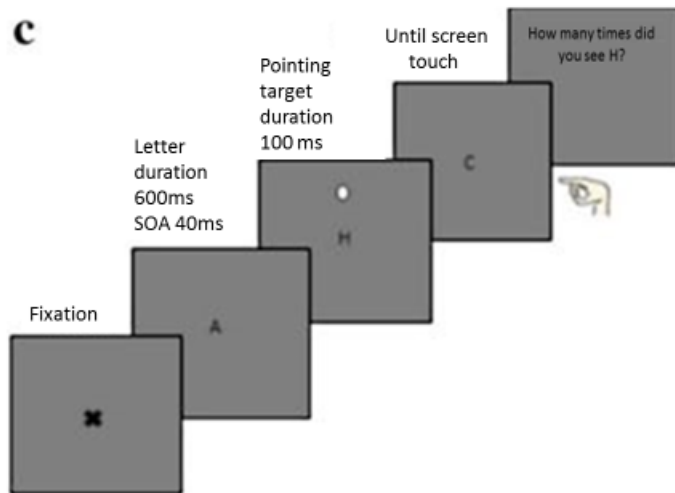
Fig. 2. Sequence of events in the baseline pointing condition (a), the experimental condition where the search task concludes simultaneously with pointing target location (PR) (b), and the experimental condition where the search task continues throughout the reach (WR) (c)

Observers were instructed to point to the dot of luminance as fast as they could as soon as they saw it using their right index finger. Stimuli appeared randomly at one of the eight possible target positions with equal probability. There were 25 pointing trials for each target position resulting in a total of 400 trials per observer. This amount was in excess of the number recommended by power analysis but was chosen to ensure enough data points remained to enable a valid analysis after trials with an incorrect search task response were removed. The final two conditions were dual-task attention, comparisons with baseline (single task) performance for each experimental element allowed a greater depth of understanding of the processes underlying task performance to be investigated. Again, observers were presented with an initial grey screen with a central fixation cross until they indicated their readiness to begin each individual trial by pressing the left-hand side mouse key with their right index finger. The two conditions can be differentiated by timing, that is, at what time in the trial the central search task ends. In one, the search task ends

simultaneously with the presentation of the pointing stimuli ensuring that target localisation and the possibility of search task disengagement occur together this means processing need only continue for part of the reach so it is identified as the part reach condition (PR) (see Fig. 2b). In the other, the search task continues until the whole reach has been completed so it has been labelled the whole reach condition (WR) (see Fig. 2c). For both conditions, observers were asked to specify the number of H's presented in the search task upon completion of the reach.

3.3.6. Outcome Measures

Pointing endpoints were assessed along two dimensions, precision (variability) and accuracy. Accuracy was the Euclidean distance from the touch response and the target location, measured in degrees of visual angle. Accuracy responses were collated for each condition and each observer. Precision was calculated as the standard deviation of this distribution.

A key part of these measurements was to quantify the amount of time required for movement preparation (ML) and the amount of time taken by the actual transport of the hand to the screen (MT). In order to achieve this distinction between ML and MT, the mouse key was pressed down indicating readiness to begin the trial and not lifted until movement commencement. Movement latency (ML) was defined as the time between the stimuli appeared on screen and when the key was released. Movement time was defined as the time between when the finger was lifted (i.e. key released) and the screen touched (MT). In addition, search tasks' results produced a count of the total number of H's presented and the observer's responses indicating how many times they perceived H in that trial.

3.4. Results

Data were processed with software written in Matlab. We then used pairwise t-tests and linear mixed models (LMM) techniques with SPSS statistical analysis software to test our hypotheses. Trials which were in excess of two standard deviations from the mean, were excluded as outliers, and trials with ML's under half a millisecond (ms) signifying anticipatory action were removed. The final stage of data cleaning involved removal of all trials with incorrect central search task response (31% of total) to ensure attentional division was under investigation. These excluded trials were further analysed by condition, eccentricity, observer ID and pointing stimuli location to ensure general equality indicating the task impacted upon the conditions in a similar way and no strong biases were evident. Analyses were conducted pooling pointing stimulus locations by eccentricity rather than individual locations in order to focus on eccentricity from central vision rather than spatial position as the outcome of interest.

The percentage of correct search task responses were analysed for each condition and by eccentricity to be used for comparative purposes. Outcome variables included timing measures along with the endpoint information; these consisted of ML, which was the time between the pointing stimulus onscreen appearance and the fingers removal from the mouse key as the pointing motion is commenced. Actual reach time (MT) was also recorded, and this consisted of the time between the fingers lift off and screen touch.

3.4.1. Search task

Initial analysis of the search task outcome measure was analysed for correct response, then pooled across observers and compared using pairwise t-tests; this resulted in lower rates of correct responses in the experimental conditions (PR, $M = 0.56$, SEM = 0.016; WR, $M = 0.48$, SEM = 0.02) than the baselines (PR, $M = 0.71$, SEM = 0.15; WR, $M = 0.8$, SEM = 0.016). This indicates there was some cost to the ability to conduct the central search task when required to make a reaching movement in the same trial. Paired samples t-tests indicate the difference between baseline and dual-task performance was statistically significant [PR, $t(936) = 7.25$, $p \leq 0.005$; WR, $t(655) = 12$, $p \leq 0.005$]. This cost was more prevalent for the WR condition [*M diff'* $(936) = 0.32$, SEM = 0.677] than for the PR condition [*M diff'* $(936) = 0.15$, SEM = 0.02], and a linear mixed models analysis confirmed a significant mean difference between PR and WR performance [*M diff'* $(936) = 0.04$, $F(1, 2,421) = 4.01$, $p = 0.04$] (Fig. 3).
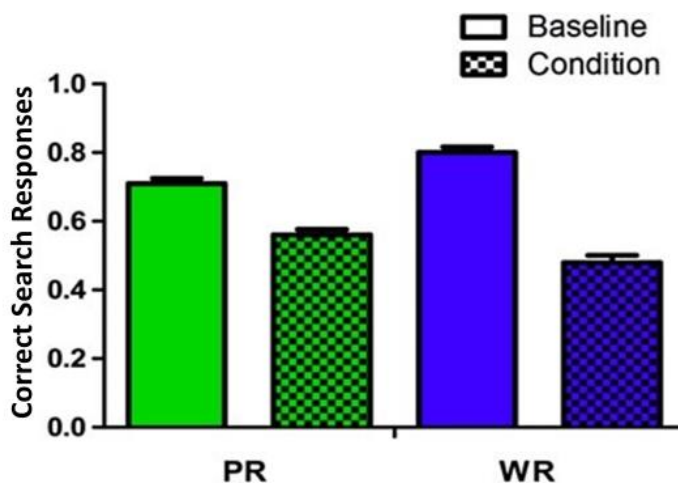
Fig. 3. Comparison between M and SEM for baseline and experimental conditions pooled across eccentricity and observers

This contributed to the investigation of dual-task costs outlined in hypothesis one and validated the experimental design. It is worth nothing that search task responses were well above the chance rate (25 %) indicating the task was not too hard but below the 100 % that

would have occurred if the task was too easy. This level of performance allows for the experimental modifications to affect the rate of correct responses while still ensuring a degree of attention was needed to successfully complete the task. The correct responses given in experimental conditions separated by eccentricity were lower at 8° (PR, $M = 0.7$, SEM = 0.19; WR, $M = 0.72$, SEM = 0.019) than 4° (PR, $M = 0.65$, SEM = 0.02; WR, $M = 0.71$, SEM = 0.019), and pairwise analysis resulted in a significant difference being found between conditions at both eccentricities [PR/WR at 4°, $t(595) = 5.9$, $p \leq 0.005$; PR/WR at 8°, $t(608) = 4.05$, $p \leq 0.005$] and between eccentricities within each condition [PR 4°/8°, $t(609) = 5.14$, $p \leq 0.005$; WR 4°/8°, $t(595) = 3.68$, $p \leq 0.005$].

3.4.2. Movement endpoints

Accuracy or the difference between the actual stimulus position and the touched endpoint position was analysed using LMM and pooled across observers. The effect of experimental condition was not statistically significant [$F(2, 2,886) = 2.08$, $p = 0.125$], but both eccentricity [$F(2, 2,886) = 41.13$, $p \leq 0.005$] and the interaction effect [$F(2, 2,886) = 3.95$, $p = 0.019$] meet the significance criteria (the traditional 0.05 was used for the initial analysis but was reduced to 0.016 to account for multiple testing when assessing pairwise comparisons). Pairwise comparison showed trials where the pointing stimulus was at 4° ($M = 0.83$, SEM = 0.018) were significantly more accurate than when the pointing stimulus was at 8° ($M = 1.00$, SEM = 0.02).

The mean difference between accuracy scores found in the different experimental conditions [$M\ diff'\ (1,483) = 0.16$, SEM = 0.05, $p \leq 0.005$] was principally driven by the greater accuracy displayed by the dual-task conditions when compared to the baseline at 4°. This indicates that the pointing endpoint was facilitated by pre-existing attentional

deployment in central vision at 4° but this was not evident at 8° where performance was comparable for all conditions (see Fig. 4). There was no difference in the degree of facilitation between PR and WR at 4°; it appears disruption to the search task does not impact pointing endpoints any differently to it continuing throughout the reach.

Analysis of precision data indicating the variability of the touch points resulted in no significant difference found between condition [$F(2, 87) = 0.14$, $p = 0.868$], eccentricity [$F(1,87) = 1.69$, $p = 0.2$], or any interaction effect [$F(2, 87) = 0.39$, $p = 0.680$], which show none of the experimental manipulations (different conditions or eccentricities) impacted upon precision (Fig. 4).
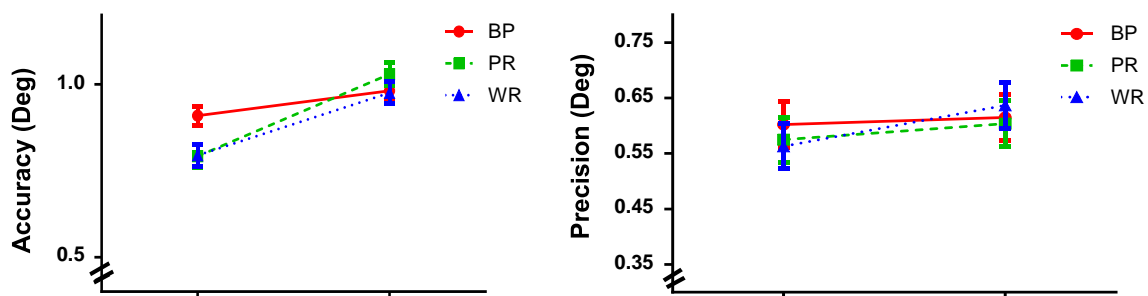
Fig. 4. Mean accuracy and precision scores for baseline (BP), part reach (PR) and whole reach (WR) conditions separated across eccentricities and pooled across observers, error bars represent SEM

Despite a non-significant finding concerning the difference between conditions for accuracy, the pattern of results suggested this might not hold true for data accompanying a pointing action to a target at 4° eccentricity. This observation, combined with the significant interaction effect, lead to the decision to run a simple analysis isolating the 4° data. For the 4° data, a significant effect of condition [$F(2, 1,483) = 6.02$, $p = 0.002$] and pairwise comparisons indicated BP was significantly less accurate than both PR [*M diff'* $(1,483) = 0.12$, SEM $= 0.04$, $p = 0.011$] and WR conditions [*M diff'* $(1,483) = 0.115$, SEM $= 0.04$, $p = 0.011$]. As more accurate touchpoints were evident under dual-task conditions, it can be

concluded that accuracy at 4° is facilitated by another task requiring attention being simultaneously conducted.

3.4.3. Time outcome measures

Analysis of ML, the time taken between target presentation and movement commencement, indicated a significant difference between experimental conditions [$F(2, 2,883) = 213.45$, $p \leq 0.005$], but not between eccentricities [$F(1, 2,883) = 0.415$, $p = 0.519$]. The interaction effect was not significant [$F(2, 2,883) = 0.238$, $p = 0.788$]. Pairwise comparisons found ML was shorter in the BP condition than in either dual-task conditions [PR, *M diff'* (1,483) = 0.07, $p \leq 0.005$; WR, *M diff'* (1,483) = 0.08, $p \leq 0.005$], which indicated the time taken to plan the movement before its commencement was negatively impacted by the presence of a central search task during processing. However, little impact was found dependent upon the continuation or disengagement of the search task during this time [*M diff'* (1,483) = 0.01, $p = 0.46$] (see Fig. 5).
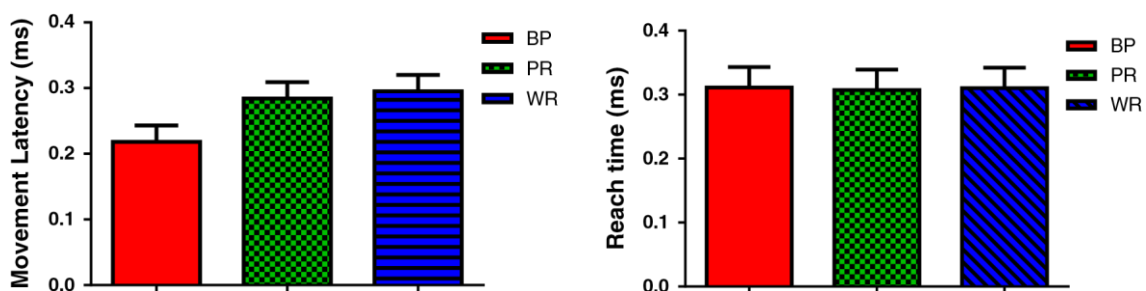
Fig. 5. Mean movement latency and movement time based upon experimental condition [baseline (BP), part reach (PR) and whole reach (WR)]

The analysis of MT, the time between the finger lift off and when it touched the screen, found no statistically significant difference between conditions [$F(2, 2,883) = 1.72$, p

= 0.179] or eccentricities [$F(1, 2{,}883) = 0.44$, $p = 0.51$]. The interaction effect was not statistically significant [$F(2, 2{,}883) = 0.21$, $p = 0.813$]. In contrast to ML, none of the experimental manipulations impacted upon the time it took to enact the reach (MT) (Fig. 5).

The experimental manipulations had differential effects on the sets of outcome measures. Accuracy was significantly affected by the attentional manipulation, but precision remained unaffected. The durations of the pre-movement planning phase (ML) were impacted by experimental manipulations while the actual time spent moving (MT) remained unaffected. Further analysis was undertaken based upon the initial findings of accuracy and a time-based outcome measure (ML) having statistically significant effects raising the possibility of a kind of speed/accuracy trade-off (Fitts 1954) inherent in the task where an increase in accuracy was associated with a decrease in ML, or the pre-movement planning time. The mean and SD of the baseline condition ML formed a range of values. Only trials, which fell within this range, were analysed from both PR and WR conditions. This would effectively hold the ML constant across conditions ensuring that the effects were not the result of differences in the pre-movement planning time.

An analysis on accuracy on this filtered dataset found that the difference between conditions was not significant [$F(2{,}755) = 0.95$, $p = 0.386$], but a statistically significant difference between eccentricities was observed [$F(1, 1{,}476) = 9.88$, $p = 0.002$] with 8° ($M = 0.957$, SEM = 0.030) being less accurate than 4° ($M = 0.830$, SEM = 0.029) (Fig. 6). The interaction effect was not statistically significant [$F(2, 1{,}477) = 1.01$, $p = 0.366$]. To summarise, when time allowed for movement planning was constrained, any effect due to condition was negated but an eccentricity effect was still observed.
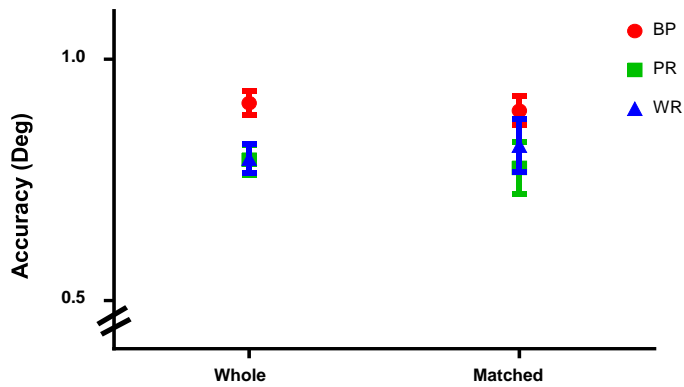
Fig. 6. Comparative view of all experimental conditions, baseline (BP), part reach (PR) and whole reach (WR) of the mean and SEM for accuracy to targets at 4° eccentricity of the whole dataset and the analysis constrained by ML (matched)

Due to the matched nature of the dataset concerning MT non-significant findings regarding differences between conditions for this variable were expected, findings for Precision and ML also continued to be non-significant. Once again, there appeared to be a difference at the 4° eccentricity, this time only between BP and PR, however, as suggested by a non-significant interaction effect, and the analysis of the 4° data revealed a non-significant difference between conditions [$F(2, 763) = 2.15$, $p = 0.118$].

3.5. Discussion

The results suggest that an interference effect was present when engaging in dual-task conditions indicating dividing attention impacted upon performance. These results support Deubel and Schneider's (1996) finding that cognitive and motor tasks have a shared attentional resource. In the current study, both tasks were affected, as performance on the central search task showed a decreased percentage of correct responses when enactment was coupled with a pointing movement. Supporting Liu et al.'s (2008) finding, ML was consistently longer under dual-task conditions, indicating that while dual-task movement took

no longer to enact (MT), it did take longer in the pre-movement planning stage (ML). However, there is some indication that this system is fundamentally different if the goal-directed movement component is a grasp. For example, Hesse et al. (2012) found dual-task interference when enacting a perceptual and grasping task for both ML and MT components of the reach. In the current study, pointing accuracy was found to be impacted by the dual-task only at 4° eccentricity and this effect was removed when pre-movement planning time was restricted. There was no effect at 8° eccentricity.

Dual-task effects were observed for both the central search task and the planning stage of the goal-directed movement. This result suggests that, at least in that stage of the movement, some shared attentional resources are evident. The dual-task cost for accuracy was negated when movement planning time was held constant, so it could have been the result of fluctuations of attention in the visual field, the result of a speed/accuracy trade-off, or the result of participant strategy in which they chose to deploy extra attentional resources to the pointing stimulus to compensate for declining acuity.

Interestingly, pointing accuracy was facilitated by dual-task conditions at 4° eccentricity, coupled with the longer ML for dual-task and the disappearance of the facilitation when conditions had ML restricted, which was achieved by restricting the analysis of trials to only the subset that had the same ML distribution as the baseline. While one might be tempted to conclude a kind of speed/accuracy trade-off was at work, no difference between conditions was found at 8°. ML times were also longer under dual-task conditions. This is consistent with the central search task biasing attention towards central vision, and providing a greater attentional facilitation at 4° than was evident at 8° (Petrov and Meleshkevich 2011). These results are consistent with van Beilen et al's. (2011) findings supporting an 'attentional window' or a region in space where spatial attention is deployed that is to some degree under voluntary control and can be modified to fit behavioural goals.

The decrease in performance between 8° and 4° suggests that there may have been a graded decrease in the attentional window but further investigation involving testing at several more eccentricities would be needed before conclusions could be drawn on the possible size of the window or if it had a gradual or sharp border.

These results suggest there is a cost to reach performance if attention is engaged away from the reach goal but this cost is associated with movement planning rather than execution. As the perceptual search task displayed a reduction in performance ability when coupled with the pointing task, the results suggest that shared resources are used during movement planning and performance of the visual search task. This is possibly related to Brown et al's. (2011) recent finding that low level motor and the early visual system may make use of the same attentional operations. The interference between variables in this study suggests they may even be drawing on the same attentional pool.

As expected, some eccentricity effects were evident, decreased accuracy was observed at 8° than at 4° and consistent with changes in visual acuity. However, eccentricity did not significantly affect precision. This may be explained by the pre-motor theory in that motor planning triggers a shift in spatial attention to the movement goal position that reduces variability in movement endpoints but is somewhat inconsistent with the decreased accuracy, which should also benefit from the attentional boost. In this context, it is possible that pointing acts like saccades by triggering a shift in spatial attention as both involve a movement plan and execution. An eccentricity effect occurring in accuracy but not precision may be the result of the fast MTs restricting updating causing a reliance upon the initial movement plan. This could impact accuracy as the initial information used to formulate the plan is encoded by cells at the two eccentricities so difference between them could be attributable to differences in acuity. The lack of updating time and the greater weighting given to the initial movement plan may have reduced variability as the initial plan was

formulated under steady conditions resulting in no eccentricity effects being found for precision. another possible underlying mechanism negating the impact of eccentricity impact on pointing accuracy could be the deployment of a greater attentional resource to the stimuli, which is furthest away which could compensate for lower acuity levels (Juola et al. 1991) and bring performance back to baseline levels; however, further investigation would be needed before this conclusion was accepted without reservation.

Neither of the timing variables exhibited an eccentricity effect. However, the central search task had fewer correct responses when the corresponding pointing action was to a target further from the central task. A greater difference between performance on the search task between 4° and 8° was observed when the search was disrupted. This difference was smaller when it continued until movement completion.

Interestingly, aspects of both tasks and therefore both visual regions, correct search identification in focal vision and accuracy in peripheral vision were negatively affected with eccentricity. However, this was unlikely to be a kind of cost sharing between the tasks or regions because accuracy was performed at the same level as the single-task baseline, suggesting that most of the cost was associated with central vision and search task performance. This could be indicative of an underlying weighting mechanism, which results in the uneven distribution of resources and so conditions impact one task to a greater extent than the other. Overall, reduced performance in the ML and search task performance could be attributed to the greater distance between the central search task and the peripheral pointing position. An eccentricity cost was observed not only in the pointing task (ML) but also with central search task performance, challenging the idea that focal vision has a primary link to spatial attention.

It was hypothesised that attentional disruption during the pre-movement planning stage may impact upon the movement endpoint, either enhancing it by allowing eye

movements and so engaging overt attention or degrading it by increasing interference by having to engage in the cessation of one task while simultaneously starting the processing of another. Neither of these predictions was strongly supported with no difference being found between the two dual-task experimental conditions for any of the movement outcomes measured. However, the percentage of correct search task responses had a greater decrement from baseline in the condition where the search continued throughout the reach suggesting that discontinuation of the search task during pointing localisation and initial planning was less of a disadvantage than when it continued to the movements completion regarding successful search task responding. This suggests that there was a one-way effect with concurrent pre-movement planning and search task continuation/ discontinuation impacting upon the search task but not movement responses. Cessation of the search task coincided with pointing target localisation and planning stage. The search task continuing throughout the reach impacted search task performance, but failed to impact pointing performance. This result suggests that attentional resources may be preferentially allocated to the movement planning at the cost of the perceptual task, consistent with the premotor theory prediction that movement planning and spatial attention are functionally equivalent.

Overall, movement enactment was surprisingly unaffected by the attention demanding search task, illustrating the robustness of the movement system. However, movement latencies (or pre-movement planning time) showed consistent and significant lengthening when the central search task was present. Time taken to execute the movement remained constant. The movements undertaken in this study were fast, and there was time for only limited online updating. It would be interesting to investigate whether planning and updating a movement shared resources or was affected by attentional manipulations in a similar way. This could be done by lengthening the reach to become a slow rather than fast reach, thus giving more time for online updating to occur. Because no difference was found between

experimental conditions, a question was also left regarding magnitude or the cognitive load of the task: would any central task which required attention have impacted on the ML in the same way or does task difficulty (or the attentional load required to perform the task) impact upon the length of time taken for pre-movement programming? This could be investigated by manipulation of the attentional load of the search task, either easier, harder or both and calculating the effect upon ML.

In this study, the presentation time of the target was designed to restrict eye movements. The letters were displayed one at a time and were briefly displayed, so that a saccade could not be performed without missing some of the letters in the string. Since trials, which had an incorrect search task response, were omitted from the analysis, it controlled for possible eye movements. This was incorporated into the experimental design to better study the effects of attention on the different visual fields (foveal and peripheral) and to ensure attention was divided rather than moving between tasks.

Overall, the results suggest attentional resources are to some degree shared between perceptual (cognitive) and movement (motor) systems resulting in reduced performance expertise in the tasks when both are undertaken simultaneously. As this deficit is primarily associated with the pre-movement planning stage of goal-directed movement, it appears that cognitive components are the primary source of the interference observed.

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4. Conclusions

The division of attention between a cognitive search task and a goal-directed motor task impacted performance suggesting a degree of shared resources between the two tasks. Dual-task impact was only observed in the planning segment of the movement (ML) but not during the reach when the hand was in motion. This allows us to conclude sharing of a pooled resource between tasks only for the planning stage of the movement. However, as all reaches were fast there was little time for updating resulting in a reliance on the initial movement plan. Conceivably this could make attentional effects on reaching time appear unaffected and so lays the groundwork for study two's investigation into attention and slow goal-directed reaching. It is possible that by restricting reaches to fast movement times reaching to the stimuli was challenging in itself. This contributes to task difficulty placing a high load on resources, as difficulty increases so do errors potentially masking small experimental effects. While the search task showed some dual-task decrement an overall attentional bias toward central vision was observed. The results of this study validated the new paradigm devised to investigate how dual-tasks impact goal-directed reaching. However, the results do strongly suggest further study is needed where the movements are slow in order to better understand the underlying mechanisms at work.

5. Preface to Paper 2

In publication one I found evidence of attentional costs dual-task costs to a reach when resources were deployed away from it. However this was only evident during the movement planning stage, reflected in the movement latency variable. Before concluding that the sharing of attentional resources between the reach and search task was limited to the planning stage of the reach, the experimental conditions under which the results were obtained must be considered. Study one only employed fast reaches, a factor that could have influenced the lack of impact found for online reaching. Movement planning has an obvious cognitive component that could share attentional resources with the cognitive central search task. The reaching stage of the movement also has a cognitive component, online updating, which could be dependent on attention. Online updating is used to correct movement trajectories once the hand is in flight, therefore maximising the time taken to make a reach also maximises the time available for updating. Fast reaches may limit the time available for updating to such a degree that any modulation of performance due to this factor would be unable to be observed. The second study therefore employs the use of slow goal-directed movements keeping all other factors constant. The major aim of this study in terms of the overall aims of the thesis is to investigate the possibility that attentional deployment to central vision could impact reaching (possibly via online updating) when moving slowly. This will allow a filling of the gap left from paper one where we were unable to conclude if dual-task effects were evident all through, or localised to specific parts of the reach.

Statement of Authorship

Title of Paper	Attentional allocation occurs during both planning and reaching phases of slow goal-directed movement
Publication Status	☐ Accepted for Publication ☐ Submitted for Publication ☑ Unpublished and Unsubmitted work written in manuscript style
Publication Details	

Principal Author

Name of Principal Author (Candidate)	Heidi Long		
Contribution to the Paper	Devised experiments, ran experiments, analysed data, writing and editing.		
Overall percentage (%)	80%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

    i.   the candidate's stated contribution to the publication is accurate (as detailed above);

    ii.   permission is granted for the candidate in include the publication in the thesis; and

    iii.   the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Anna Ma-Wyatt		
Contribution to the Paper	Devised experiments, assisted in analysis and writing.		
Signature		Date	1/3/17

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6. Paper Two; Attentional allocation occurs during both planning and reaching phases of slow goal-directed movement

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Words: 5352

Figures: 5

6.1. Abstract

Goal-directed movements are particularly important to daily life as they provide a direct way to interact with the environment. Enactment of these movements requires sensory, cognitive and motor elements to form a goal-directed movement system. When a movement is segmented the pre-movement planning time appears to share attentional resources with a cognitive task under dual-task conditions. However, the role of attention to online updating remains unresolved. By using slow movements to maximise updating we hope to directly address this issue. We used a dual-task paradigm to investigate how resources can be deployed during a slow, goal directed movement. Participants completed a central search task while also making a slow pointing movement to a peripheral target. Results indicated that the planning and execution of the reach required attentional resources when moving slowly. This suggests attention can be flexibly deployed in response to different task demands. When the movement required less attentional resources, more attention was allocated to the central task which could then be performed at single-task baseline levels.

6.2. Introduction

6.2.1. Attention for goal directed movements and a secondary task – a common resource?

People use goal-directed movements to interact with and manipulate objects in their environment. Completing a goal-directed movement involves visual information about the target location as well as sensory and motor feedback during the reach (e.g. Sarglegna, Blouin, Vecher, Bresciani, Bourdin & Gauthier, 2003). There is also considerable evidence to suggest that attention plays a significant role in planning and executing a goal-directed movement. For example, attention is thought to be vital for selection of the goal of the reach (e.g. Baldauf & Deubel, 2008) and the use of focal attention during an odd coloured target search task can reduce the reach time of a goal-directed movement (Song & Nakayama, 2006). In a natural environment, goal-directed movements are often carried out concurrently with other tasks suggesting attentional resources need to be flexible.

Attention can be divided and the idea of multitasking rests on this premise. However, it is unclear whether dividing attention between a cognitive and a motor task draws on a single attentional resource, or whether modality-specific attentional resources exist (Jonikaitis, Schubert & Deubel, 2010). Moore (2006) reported that brain neuroimaging and single cell recording studies have found both shared and individual parts in the attentional network are assigned to overt (coupled with an eye movement) and covert attention (attention deployed without an eye movement). However, it is as yet unclear how attentional resources are shared when carrying out dual-tasks that require responses across central and peripheral visual regions. For example if attention is directed away from the movement target using a dual-task paradigm, movement latency increases when reaching rapidly (Long & Ma-Wyatt, 2014), suggesting that attention and movement planning are coupled. Despite these findings

several questions remain regarding how divided attention impacts the enactment of goal-directed movements and how the deployment of attention occurs across different areas of visual space during a divided attention task.

6.2.2. The changes in attention across visual space

There are fundamental differences in stimulus encoding and processing in central and peripheral vision and these differences can impact goal-directed movement systems. The composition and density of photoreceptors changes with eccentricity resulting in reduced perceptual performance consistent with a reduction of visual acuity with eccentricity (Anstis, 1998). However, not all processing differences conform to what could be expected from differences in photoreceptor density alone (Stephenson, Knapp & Braddick, 1991) and some of these changes may also be due to attention selectively enhancing processing. The effects of attention have been reported to depend upon distance from the central fixation point (Baldauf & Deubel, 2008; Juola, Bouwhius, Cooper & Warner, 1991; McKela, Rovamo & Whitaker, 1997) and attention has been suggested as a mechanism that can reduce the impact of eccentricity (Juola et al. 1991).

Some attentional processes remain constant across eccentricities, for instance in an investigation into the impact of covert attention on a complex visual search task, discriminability was found to increase and information processing was faster when covert attention was applied to the task regardless of the eccentricity it appeared at (Carrasco, Giordano & McElree, 2006). The movement updating mechanism is operational throughout the reach (Saunders & Knill, 2005) so it is likely both visual regions contribute to updating information. However, the nature of the relationship between eccentricity and online updating (if any) has yet to be resolved. While there have been suggestions of a possible link between deficits in peripheral vision and updating deficits, this issue is still open to debate

(Gaveau, Pisella, Priot, Fukui, Rossetti, Pelisson & Prablanc, 2014). As attentional effects fluctuate with eccentricity for some tasks but not others the distribution of attention is dependent on task demands. In consideration of this the current study into the impact of task dependant attentional deployment on peripheral pointing will employ a design which tests two target eccentricities.

6.2.3. Movement speed and online updating

In a past study we found attentional effects on movement latency (ML, the time between target onset and motor action) reflecting attentional involvement in the planning stage of the movement (Long & Ma-Wyatt, 2014). However the lack of a relationship between attentional modulation and reach time (RT, from finger lift-off to movement completion) needs further testing to be substantiated as past findings conflict. For example, Hesse, Schenk and Deubel (2012) found attention impacted both ML and RT phases of the movement, while Liu, Chua and Enns (2008) found impact restricted to the ML movement phase. Using rapid movements have limit the possible dual-task effects on the outcome of a goal-directed movement, since there is limited time for the integration of online feedback during a rapid goal-directed movement (Gordon, Ghilardi & Ghez, 1994). In this study we investigate how a dual-task affects performance of a slow goal-directed movement. The increased reach time ensures there is ample time for online updating of the movement trajectory and to investigate how divided attention impacts goal-directed movements.

The impact of feedback on overall reach performance fluctuates with reach parameters. While feedback can be used to increase endpoint accuracy, it may be of limited use when engaging in fast movements (Gordon, Ghilardi & Ghez, 1994). Fast reaching speeds limit the time available to gather updating information, specifically the online updating system needs 150ms to process the relevant information, amend the original

movement plan and commence adjustment of the movement (Kane, Wade & Ma-Wyatt, 2011). The impact of attention may not be stable across feedforward and feedback processes. Therefore it is important to look at the different phases of the movement. Movement planning takes place predominantly before the motor action has begun. Costs to the planning phase can be investigated using movement latency (ML) or the time between presentation of the visual target and the time the motor response begins (Liu, Chua & Enn's 2008; Barthelemy & Boulinguez 2001; Long & Ma-Wyatt, 2014). The reach time (RT) or the time between the start and the finish of the movement, covers phases of the movement from the early stages of the reach (known to be reliant on movement planning) through to the later stages of the reach as the hand decelerates towards the target and online feedback about the relative position of the target and hand can be used to update online trajectory (Soechting & Lacquaniti, 1981).

Updating and movement correction can occur without conscious awareness (Saunders & Knill, 2003; Gaveau et al. 2014) and as such may be an automatic pre-attentive response which remains unaffected by experimental manipulations to attention. Sarlegna and Mutha (2014) found that a cognitively demanding task undertaken while pointing did not impact updating or movement correction consistent with updating being pre-attentive. However suppression of online correction has been found to be cognitively demanding (McIntosh, Mulroue & Brockmole, 2010) supporting the idea that updating has a cognitive component. Gaveau et al. (2014) found observers were engaging in voluntary correction which suggests the possibility that attention may influence online updating when there is time to engage conscious movement correction strategies. It is also possible that updating and corrections of goal-directed movements that appear unconscious may still tap a low level attentional resource (Gaveau et al., 2014). These discrepancies regarding the role of attention for online updating highlight the need for further investigation into this area.

6.2.4. Differences in movement speed could provide novel insights into divided attention for goal-directed movements

Movement speed impacts online updating as the more time there is for feedback, the more correction is possible (Saunders & Knill, 2003). Additionally slow movement trajectories can be assessed for error by both central and peripheral vision (Bedard & Proteau, 2004). The speed of the movement also impacts the approach taken to enacting goal-directed movements. Hanson et al. (2006) found more time was allocated to pre-movement planning when the observer knew the information available for updating (in this case vision of the hand) during the reach would be limited. So does attention operate in the same way in both fast and slow movement systems? As a flexible resource, it seems reasonable that attentional resources are deployed differently dependent on movement speed, but findings in this area so far are not consistent. Saunders and Knill (2003) reported that the duration of ML (reflecting movement planning processes) remained stable under fast and slow movement conditions, conversely Hanson et al. (2006) found a decrease in ML with fast reaches.

In the present study, we used a dual-task paradigm to explore the relationship between two tasks, one processed in central vision (an alphanumeric search task) and one in the periphery (a goal-directed pointing movement). Since both spatial localisation and alphanumeric search tasks have been found to require attention, dual-task/divided attention conditions should show impaired performance if the two tasks draw on the same attentional resource. However if the tasks draw on different attentional resources, there would be no interference produced by doing the two tasks at once and performance in dual-task conditions would be no worse than in single task baseline conditions.

Observers were asked to reach slowly maximising the time for online updating. Studies of goal-directed movement and attention, using a dual-task paradigm involving a perceptual and a motor task have not yet formed a consensus about whether another task

demanding attention impacts both the planning and online updating of a movement (Hesse, Schenk & Deubel 2012) or if the impact is restricted to the planning stage (Liu, Chua & Enns 2008).

6.2.5. The current study

In these experiments we aim to clarify how a dual-task impacts the deployment of attention during a slow reaching movement. The overarching question is the cost of deploying attention during a movement and what is revealed about the attentional resources available for goal-directed movements. We first investigate the dual-task costs (or lack thereof) between a central search task and a peripheral goal-directed pointing movement on task performance. Specifically, it is expected that consistent with findings of dual-task costs to ML when reaching fast (Hanson et al., 2006; Liu, Chua & Enns, 2008; Long & Ma-Wyatt, 2014), the ML of slow movements will also incur dual-task costs. If similar results are seen in these experiments it will suggest that the planning phase is affected by dual-task conditions regardless of reach speed.

Secondly, we will measure how completing a dual-task affects performance on targets at different eccentricities from the central search task. Based on the decrease in acuity with increasing eccentricity (Anstis, 1998) and attentional deployment being dependant on distance from central vision (Baldauf & Deubel, 2008; Juola et al., 1991; McKela, Rovamo & Whitaker, 1997), it is likely that increased eccentricity will result in decreased pointing performance.

Finally, the impact of the dual-task on online updating will be investigated by examining differences in overall reach time (RT). It is somewhat difficult to predict what impact (if any) will be found. If updating is pre-attentive (Saunders & Knill, 2003; Sarlegna

& Mutha, 2014) and has no need to draw on attentional resources the attentional conditions will not impact reach time and dual-task conditions will be similar to baseline times such as has been found to be the case with fast reaches (with limited time to update) (Long & Ma-Wyatt, 2014). If the online updating is cognitively demanding (McIntosh, Mulroue & Brockmole, 2010) and taps into an attentional resource (Gaveau et al., 2014) we may see a difference between baseline and dual-task performance for reach time.

6.3. Methods

6.3.1. Participants

Five observers (N=5) four female and one male, age range 22 to 32 participated in all stages of the experiment. Three were experienced psychophysical observers and two were trained for this experiment, all five were naive to the purposes of the experiment. All had normal (or corrected to normal) vision, were right hand dominant and therefore responded with their right hand. Ethics approval was granted by the Human Ethics of the University of Adelaide. Participants gave informed consent and were free to withdraw at any time without penalty.

6.3.2. Materials

A 17" ELO touchscreen monitor was used to present the experiment. The screen ran with a resolution of 1024x768 pixels and a refresh rate of 60hz. Stimuli were presented in one of 8 possible target positions (per trial), target positions were 90° apart (at points consistent with 12, 3, 6 and 9 o'clock on a clockface) and at two eccentricities, 8° and 4° degrees from the central fixation point (see Figure 1).
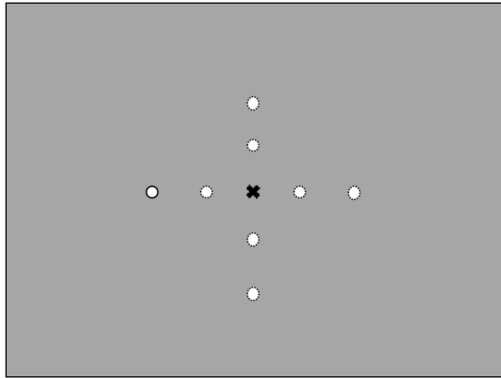
Figure 1 On any given trial, the pointing target appeared at 1 of these 8 locations with equal probability

Participants were seated at a table which held the computer screen and used a chin rest. The viewing distance was 40cm. The mouse was positioned 40cm from the centre of the computer monitor at a 20º angle to the right. The target of the goal-directed movement was a high contrast (43% Michelson contrast), high luminance spot that was shown for 100ms and was 0.5º in diameter.

Experiments were custom written and run in Matlab utilising the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Data were analysed offline using SPSS and Matlab. Target location and the location of the touch response were recorded. As was the time between stimulus presentation and movement commencement (Movement Latency, ML) and the time between movement commencement and touching the screen (Reach Time, RT). The number of target letters presented and the participant's response to how many target letters were seen was also recorded for analysis.

6.3.3. Procedure

The experiment was conducted in a dark, quiet room to minimise attentional shifts due to external stimuli unaccounted for by the experimental protocol. At the commencement

of each testing session a training block of 100 trials which gave feedback ('Too Fast!') if a reach (the whole of the movement, ML and RT) was conducted too quickly (less than 1.5sec). This ensured reaching time was sufficient to allow maximum time for online updating of the movement. Participants were given verbal instructions along with a practice set of each condition before testing. Participants were offered extra practice sets if desired. The letter string ('A' to 'J') consisted of a series of high contrast letters (with the same properties as the pointing stimulus) were shown at central vision on a grey screen. Each letter was presented for 16ms with a 16ms gap between presentations to eradicate backward masking effects. The letters were presented one at a time consistent with visual search has being processed serially (Wolfe, 2003).

The pointing stimulus was a high contrast dot presented in peripheral vision (see Figure 1) whose physical properties were designed to capture the available peripheral attention in accordance with Franconeri, Hollingworth and Simons' (2005) finding that luminance contrast produces bottom-up attentional capture. The target was presented only briefly (100ms) to ensure localisation was conducted using peripheral vision and also prevented attentional shifts (Deubel, et al., 1998) that would benefit the movement. The pointing targets circular array around a central fixation point was used by past studies and prevents a significant response or left/right bias (Ma-Wyatt and McKee, 2006, 2007; Song, Takahashi, & McPeek, 2007). It was also chosen to remain consistent with Juola, Bouwhius, Cooper, and Warner's (1991) finding of attentional distribution in rings moving out around a focal point.

6.3.4. General Procedure

At the beginning of each trial the participant was instructed to first wait for a dark central fixation dot to appear after which they were free to commence when ready. The trial

began when the right mouse button was pressed, this remained down until finger lift-off in response to the pointing target. Experimental and baseline conditions were presented in an individually randomised order for each participant and the order of conditions was counterbalanced across participants to negate any practice or order effects.

6.3.5. Conditions

The study was a repeated measures design therefore each participant provided their own baseline. Each component of the design was performed under single-task baseline conditions for comparative analysis with the dual-task experimental conditions. Total experimental time was approximately 3-4 hours conducted in 30 minute sessions over several days in order to reduce the chance of muscle or attentional fatigue.

6.3.6. Baseline conditions

Two baseline search task conditions were tested. The baselines were either 6 or 20 letters long consistent with the experimental condition search task lengths. In these conditions, the participant completed each search task without a concurrent reach. At the beginning of each trial the participant indicated they were ready to start by pressing the right mouse key. After completion of the letter string 'How many times did you see 'H'? appeared and the participant responded to the question using the number array on the keyboard.

Baseline performance of the goal-directed movement under single task undivided attention conditions was also obtained where participants pointed without doing a concurrent search task. Once a trial commenced the central fixation dot disappeared and a pointing stimulus was presented. Observers were asked to make a slow goal-directed movement to the remembered stimuli position (Figure 2a). Presentation of the pointing target was displayed

randomly at one of the eight possible target positions with equal probability. There were 150 pointing trials for each target position, a total of 1200 trials per observer, per condition. This buffered against the necessity of removing a number of trials due to incorrect search responses. Experimental power was obtained due to the large number of trials representing *N* rather than the number of participants.
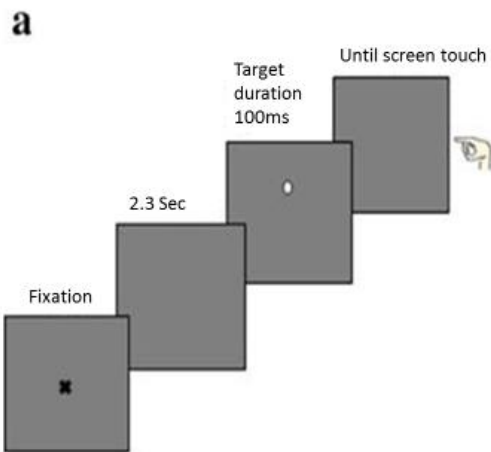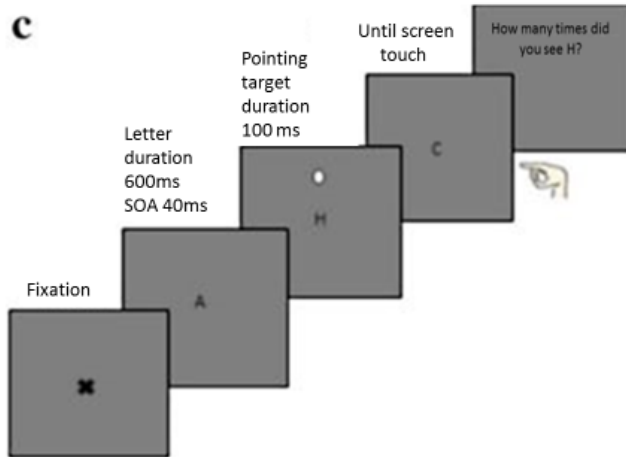
Figure 2 Sequence of events in the baseline goal-directed movement condition (BP); the sequence of events in the Part Reach (PR) condition, when the search task concludes concurrently with the presentation of the pointing stimulus; and the sequence of events in the Whole Reach (WR) condition, when the search task continues throughout the reach

6.3.7. Experimental conditions

There were two dual-task experimental conditions (requiring attentional division), both involved a central search task and a pointing movement to a peripheral location. The two conditions can be differentiated by where in the trial the central search task ends. In one condition the search task stopped simultaneously with the pointing target presentation, this was identified as the Part Reach (PR) condition (Figure 2b). In the whole reach (WR) condition the search task was not completed until after the reach finished (see Figure 2c). For both conditions observers were asked to specify the number of H's presented in the search task upon completion of the reach.

6.4. Results

Trials were excluded if they were in excess of two standard deviations from the mean of any variable (pointing accuracy, ML or RT). The final stage of data cleaning involved removal of all trials with incorrect central search task response to ensure attentional division. A p-value of 0.05 was used for the initial analysis using LMM but was adjusted to 0.016 to account for multiple testing when assessing pairwise comparisons.

6.4.1. Search Task

Data were pooled across observers and performance between conditions compared using pairwise t–tests. Little difference was found between the mean correct response on the single baseline conditions [PR, M=73.14, SEM=1.92; WR, M=56.75, SEM=6.25], or the dual-task experimental conditions [PR, M=74.21, SEM=1.88; WR, M=56.75, SEM=5.33] (see figure 3). This suggested there was no cost to the search task when having to make a goal-directed movement in the same trial. This was confirmed by the results of a t-test which found there was no significant difference between baseline and dual-task performance for either PR or WR conditions. However, performance on the two lengths of search task (a string of 6 letters for PR, 20 letters for the WR condition) were significantly different for both baseline conditions [M *diff'*=16.39, SEM=4.91, p=0.03] and during dual-task conditions [M *diff'*=13.92, SEM=3.54, p=0.02]. Overall the results suggest that performance on the central search task was not impacted by a secondary task when that secondary task was a goal-directed movement with ample time for online updating but it was impacted by the length of the alphanumeric string.
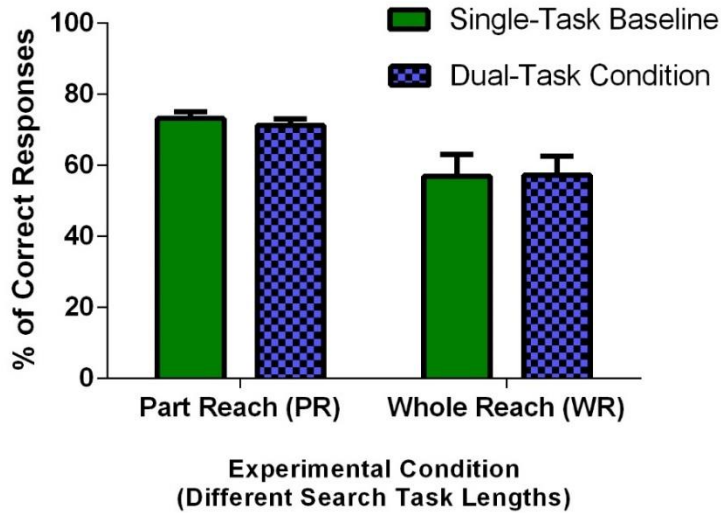
Figure 3 Comparison of the mean percentage correct search task responses for baseline and experimental conditions pooled across eccentricity and observers. Error bars represent one standard error of the mean.

6.4.2. Accuracy and precision of movement endpoints

Accuracy, the Euclidean distance from the touch response and the target location (measured in degrees of visual angle) was calculated for each trial, for each observer. These data were collated across observers and analysed using Linear Mixed Models Analysis (LMM). The interaction effect was significant [$F(2, 2546)=6.15$, $p=0.002$], as were both eccentricity [$F(1, 2546)=52.83$, $p=<.001$] and condition [$F(2, 2546)=32.53$, $p=<.001$]. Accuracy was significantly better at 4° [$M=0.54$, SEM=0.07] than when the pointing target was at 8° [$M=0.66$, SEM=.07] [$Mdiff(792)=.49$, SEM=.12, $p<.001$] (see Figure 4). Pairwise comparisons indicated performance in the PR condition was significantly different to baseline [$Mdiff(2546)=.15$, SEM=.02, $p<.001$] and WR accuracy [$Mdiff(2546)=.14$, SEM=.02, $p<.001$]. Accuracy was not significantly different between the WR and BP [$Mdiff(2546)=.01$, SEM=.02, $p=1$].
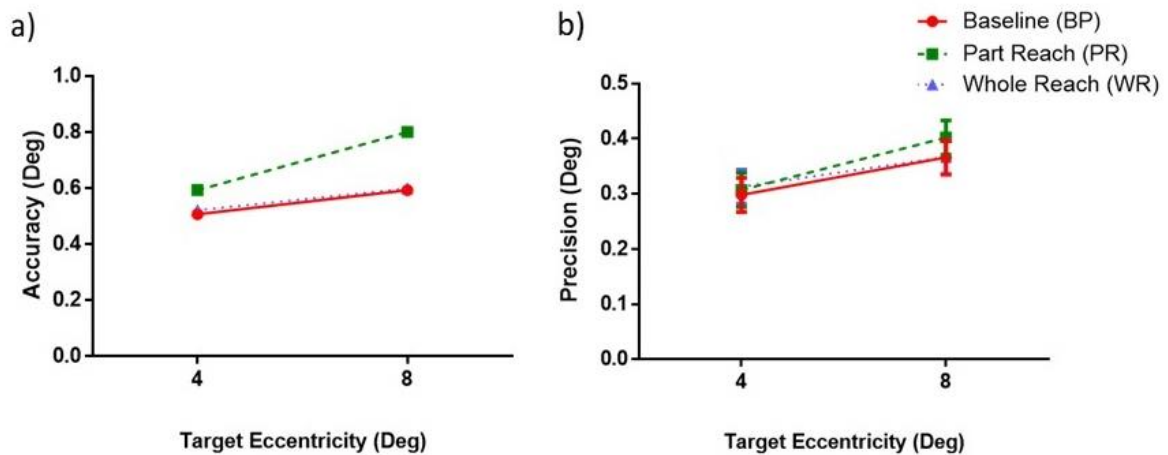
Figure 4 Accuracy (a) and Precision (b) of endpoints for baseline (BP), part reach (PR) and whole reach (WR) conditions, pooled across observers. Error bars represent SEM, symbols sometimes bigger than error bars.

Precision was calculated as the standard deviation of the accuracy scores for each participant, at each target location (Long & Ma-Wyatt, 2014). Data was then pooled across participants for LMM analysis. There was no significant difference between conditions [$F(2, 110)=0.95$, $p=0.39$], or interaction effect [$F(2, 110)=0.8$, $p=0.45$]. However, the main effect for eccentricity was statistically significant [$F(1, 110)=28.82$, $p<0.001$]. Precision at 4° eccentricity [$M=0.31$, SEM=0.03] was significantly less than at eight degrees [$M=0.38$, SEM=0.03] [$Mdiff(63)=.54$, SEM=.21, $p=.013$] (see Figure 4).

Both endpoint measures were impacted by experimental conditions. There was a cost to accuracy if search completion coincided with pointing target appearance. No cost was evident when the search continued throughout the movement. Precision reflected the variability of the movement endpoints was not impacted by experimental condition, however, pointing was less precise with increasing eccentricity.

6.4.3. Time Outcome Measures

Analysis of ML indicated a significant difference between experimental conditions [$F(2, 2546)=42.01$, $p<0.001$] and eccentricities [$F(1, 2546)=4.12$, $p=0.04$] but no interaction effect [$F(2, 2546)=1.32$, $p=0.27$]. Pairwise comparisons found ML was significantly shorter in BP than either of the dual-task conditions [PR; *M diff'*=0.06, SEM=0.01, $p=<0.001$: WR; *M diff'*=0.04, SEM=0.01, $p=<0.001$] which indicated the time taken to plan the movement was negatively impacted by a central task during processing. The difference between PR and WR conditions was not significant [*M diff'*=0.02, SEM=0.01, $p=0.07$] so continuation or disengagement of the search task had little if any impact on ML (see Figure 5).

The analysis of RT, found a significant main effect for condition [$F(2, 2546)=188.32$, $p<0.001$], but eccentricity [$F(1, 2546)=1.01$, $p=0.31$] and the interaction effect [$F(2, 2546)=0.47$, $p=0.63$] were not significant. RT was longest in the BP condition [$M=1.07$, SEM=0.2], followed by PR [$M=0.97$, SEM=0.2] then WR [$M=0.94$, SEM=0.2] (see Figure 5). Despite the large standard errors, pairwise comparisons found all conditions to be significantly different from each other, BP was significantly different from PR [*Mdiff*(2546)=.1, SEM=.01, $p<.001$] and WR [*Mdiff*(2546)=.13, SEM=.01, $p<.001$] the dual-task conditions PR and WR were also different from each other [*Mdiff*(2546)=.03, SEM=.01, $p=.001$].
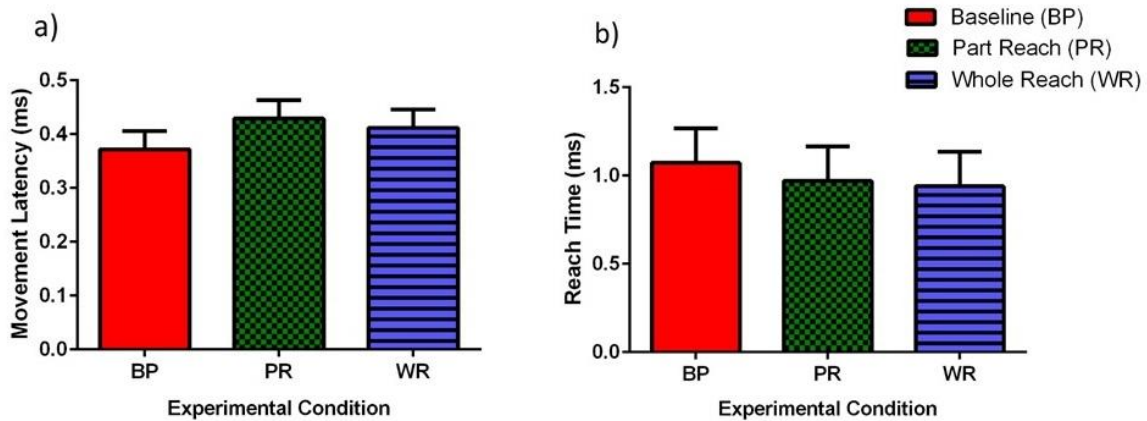
Figure 5 Comparison of the mean times for movement latency (ML) and reach time (RT) for baseline (BP), part reach (PR) and whole reach (WR) conditions pooled across observers. Error bars represent one SEM

6.5. Discussion

6.5.1. Dual-task impact when completing a motor and cognitive task simultaneously

Simultaneous performance of a search task and slow pointing impacted motor performance but not the cognitively based search responses. As search performance was not impacted by dual-task conditions it was concluded that when a participant has ample time to make a reach there is no need for attention to be deployed away from central vision.

Dual-task costs were present in endpoint accuracy but only when the central task stopped concurrent with the pointing target's appearance (PR). If the central task was consistent throughout the reach (WR) movement endpoints were as accurate as produced under single-task conditions (BP). Dual-task conditions did not impact on the precision of the movement endpoint.

ML were slower in dual-task conditions (PR & WR) compared to the baseline condition. This result is consistent with earlier findings using the same design, but with fast goal directed movements (Long & Ma-Wyatt, 2014). Reach time (RT) was also impacted by

dual-task conditions but not in the direction intuitively expected. When given the opportunity to modulate the speed of their movements to be 'slow', participants made faster reaches under dual-task conditions. Modulation of the motor task by dual-task conditions is consistent with shared attentional resources. This supports Deubel and Schneider's (1996) finding of shared resources between a visual discrimination task and an eye movement but expands it to include reaching movements.

6.5.2. The impact of initial target eccentricity on pointing during a dual task

We also investigated the impact of initial target eccentricity on reach performance. Both accuracy and precision of endpoints were significantly impacted by the pointing targets eccentricity (4º or 8º). As predicted greater target eccentricity was associated with poorer endpoint performance. The measures of movement time (ML and RT) were unaffected by eccentricity. Performance of the central search task was also unaffected by the eccentricity of the accompanying goal-directed movement.

While accuracy was consistently lower as eccentricity increased, this change in performance was more marked for the PR conditions compared to the baseline and WR conditions. This pattern indicates a differential decline in performance at target eccentricities with these dual-task conditions. Despite the finding that peripheral information can be degraded by the presence of a stimulus in central vision (Mackeben, 1999; Salvemini, Stewart & Purcell, 1996), the differential impact of eccentricity on movement endpoints is unlikely to be attributable to only this source of localisation error. If it were both conditions would show the effect, however, while the condition where the search task continued throughout the reach (WR) was performed at baseline level and only the condition where the search task stopped when the pointing target was shown (PR) showed an effect.

The eccentricity effects displayed by movement endpoints could be attributed to an 'attentional window' or the region of visual space over which sudden visual onsets capture attention. The size and spread of the window is at least to a degree under conscious, goal driven control (van Beilen, Renken, Groenewold & Comelissen, 2011). Eccentricity decrements would be consistent with a graded attentional window as proposed by Petrov and Meleshkevich (2011) but the exact nature of the differences in attentional deployment remains unclear given that only two eccentricities were investigated.

6.5.3. Online updating, attention and the dual-task system

Analysis investigated the relationship between online updating and attention. As the slow reach time increased the time available for updating the movement, it maximised the chance of the results reflecting the impact of the attentional experimental manipulations when combined with the updating process. Stimuli in central vision can degrade performance in the periphery (Mackeben, 1999; Salvemini, Stewart & Purcell, 1996). Despite this it can be reasonably expected that online updating of the movement will occur despite the presence of the central search task since past studies have found updating of a movement can still occur while engaged in a secondary search task (Sarglena & Mutha, 2014). Restriction of visual feedback including information about the position of the hand can reduce endpoint precision when pointing to a briefly presented target (Ma-Wyatt & McKee, 2007), indicating that even during rapid movements visual feedback can be used for online control.

Reach time was modulated by the different experimental conditions, which manipulated the attention distributed between the dual-tasks. This result suggests that online updating can be modulated by attention and suggests that any conclusion that it operates independently from attention might need further investigation (Saunders & Knill, 2003; Sarlegna & Mutha, 2014). Our findings are consistent with updating containing an element

of cognitive demand (McIntosh, Mulroue & Brockmole, 2010) and supports Gaveau et al's. (2004) conclusion that updating taps an attentional resource.

6.5.6. Conclusions

We found attentional resources were utilised at all stages of goal-directed movement, as shown by the dual-task impact on both planning (ML) and the executing of the reach (RT). Online updating occurs during the execution of the reach so the results also suggest that attention can modulate this aspect of the reach. It is possible the decrement in endpoint performance results from a graded attentional window, where after attention is preferentially deployed to central vision it anchors attention which then reduces attentional deployment with distance from the central region.

Overall the results support Makela, Rovamo and Whitaker's (1997) finding that under dual-task conditions (when one task is in central vision and one in the periphery) peripheral task performance exhibits a decrement when the central task requires concentration. It is possible that disengaging attention from the central location when the search task ended increased the load associated with dual-task performance resulting in the PR condition being impacted by experimental manipulation while WR remained unaffected. This issue is unresolved as yet and along with the grading structure of the attentional window provides an interesting issue for future studies to explore.

Slow reach conditions maximise the updating component of the dual-task system as reflected by the reach time of the movement. As reach time was significantly impacted by dual-task conditions that manipulated attention, it can be concluded that online updating is impacted by attention and this in turn suggests a possible cognitive component to the updating mechanism. Dual-task conditions resulted in a reduction of RT compared to baseline levels. This result was difficult to explain given the current paradigm but the

possibility of dual-task conditions placing stress upon the system triggering an unconscious hurry to complete the movement was raised as speculation.

When reaching slowly, demands on the attentional system were reduced so that only the pointing task was impacted while the search task was performed at baseline levels. This supports the suggestion that attention is preferentially deployed to central vision since when demands on the attentional resources were reduced (by slow movement speeds): the central search task was performed at optimal baseline levels but reaching was not. Eccentricity impacted reaching endpoint location but movement time measures remained constant. Under the experimental conditions investigated decreases in accuracy with eccentricity may result from attentional demands on ML while precision reflects demands on the updating system. Resulting in an eccentricity effect being found for precision under slow reach conditions but this may not be the case for fast reaches with their limited updating component.

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7. Conclusions

No dual-task costs were observed for search task performance suggesting that slow goal-directed reaching is not costly enough to deploy attention away from central vision. It also supports and strengthens the finding in study one of preferential attentional allocation to central vision. Slower reaching times were paired with slow movement latencies despite the instruction to point as soon as the target was perceived. This maximising of initial information coupled with ample time for online updating is reflected in high rates of endpoint accuracy. The greater eccentricity a target appeared at the less accurate the movement's endpoint. When taken with the attentional bias at central vision, this is suggestive of a graded attentional window where attentional deployment lessens as one moves away from central vision. Dual-task effects were found for reach times suggesting shared resources between the two tasks at this time. A comparison of results between studies one (fast reaching) and two (slow reaching) show different patterns of results dependant on task demands. However, as they have not been explicitly tested against one another firm conclusions cannot yet be drawn. This is one of the issues to be addressed by study three. This study contributes to the overall aims of the thesis by confirming that attention is utilised at all stages of goal-directed movements. Differences in attentional allocation to different regions in visual space illustrate the flexibility of the attentional deployment in response to task demands. In order to more fully understand the impact of task demands study three employs a manipulation of the search task to expand on the previous findings that have been based on manipulations to aspects of the movement task.

8. Preface to Paper 3

Thus far in our journey to better understand the relationship between attention and the goal-directed movements system under dual-task conditions, it is clear resource allocation differs with task demands. We have found attention to impact both the pre-movement planning stage, expressed in movement latency (fast reaching, paper 1) and updating during online reaching (slow reaching, paper 2). These studies have focused on the manipulation of movement speed but a direct comparison between speeds as a task demand has yet to be done.

The investigation of load is the next logical step in the question addressed by this thesis. Previous work has varied the speed of goal-directed movements but as a dual-task paradigm was being employed two tasks were performed simultaneously. The second task, a central search task remained unchanged. Task load is a measure of task difficulty: as load increases so too does the attentional allocation required for task completion. Based on this premise it can be concluded that in order to manipulate the attention required by the search, a method that changes the difficulty of the central task could do so by manipulating its load.

This study has two major tasks to achieve in terms of the overall goals of the thesis. Firstly a direct comparison between fast and slow goal-directed movements allowing for a better understanding of the dynamic interplay of factors used to achieve these movements. Furthermore it aims to investigate the manipulation of task load on goal-directed movements. Factors underlying these movements such as vision and attention have been found to be impacted by load manipulations leading to the implicit idea that load impacts goal-directed movements, however explicit investigations need to be done.

Statement of Authorship

Title of Paper	Movement speed provides a more consistent manipulation of task load for goal directed movements than cognitive load paradigms
Publication Status	☐ Accepted for Publication ☐ Submitted for Publication ☑ Unpublished and Unsubmitted work written in manuscript style
Publication Details	

Principal Author

Name of Principal Author (Candidate)	Heidi Long	
Contribution to the Paper	Devised experiments, ran experiments, analysed data, writing and editing.	
Overall percentage (%)	80%	
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.	
Signature		Date

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

   i.   the candidate's stated contribution to the publication is accurate (as detailed above);

   ii.   permission is granted for the candidate in include the publication in the thesis; and

   iii.   the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Anna Ma-Wyatt	
Contribution to the Paper	Devised experiments, assisted in analysis and writing.	
Signature		Date 1/3/17

Name of Co-Author		
Contribution to the Paper		
Signature		Date 1/3/17

Please cut and paste additional co-author panels here as required.

9. Paper Three; Movement Speed provides a more Consistent Manipulation of Task Load for Goal-Directed Movements than Cognitive Load Paradigms

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Words: 9972

Figures: 12

9.1. Abstract

People often make hand movements while also attending to another location or carrying out another task. These other tasks can be of varying difficulty and can be conceptualised as increasing cognitive load. We investigated how cognitive load and movement speed, two key variables that often modulate hand movements in daily activities, impact performance of goal directed movements. We used a dual-task paradigm that allowed us to gauge the distribution of attentional resources between a central search task and a peripheral pointing movement. The central search task had high and low-load conditions. Movements were either fast or slow, and the target could appear at one of two eccentricities, 4º or 8º from central fixation. We measured search task performance, movement latency, movement time, reach accuracy and precision. Analysis of the search task validated the load manipulation; low-load searches were performed better. Consistent with previous work there was also preferential attentional allocation at central vision. An analysis of experimental condition and high/low-load conditions (holding speed constant) on movement performance found the load of the search task had little impact on pointing outcomes. However, pointing performance was significantly affected by conducting a dual-task compared to conditions in which no dual-task was completed. The influence of the time that the target appeared (search task disengagement during localisation compared to continuation) was found to impact reach outcome measures and a consistent impact due to eccentricity was also evident. Slow movements produced more accurate reach endpoint responses and faster reaches were associated with faster movement latencies. Altogether, the results indicate that changing cognitive load had little impact on movement outcomes but movement speed did significantly modulate outcomes. It seems modulation of goal-directed movement load is better achieved by varying movement speed rather than by manipulations of cognitive complexity.

9.2. Introduction

Around the time a movement is initiated attention shifts to the goal of the movement (Baldauf, Wolf & Deubel, 2006) and increased attention can result in the faster production of these movements (Song & Nakayama, 2006). The effects of attention on goal-directed movement can be modulated by distance from the central fixation point (eccentricity) (Baldauf & Deubel, 2008; Juola, Bouwhius, Cooper & Warner, 1991; McKela, Rovamo & Whitaker, 1997). Recent work also suggests that the spatiotemporal profile of this attentional shift varies relative to the position of the target (Stewart & Ma-Wyatt, 2015). In daily life, people often make movements while carrying out another task or also attending to another location. This problem of varying the amount of attention available for two tasks has been conceptualised as cognitive load. The complexity of the task (or its 'load') has been widely studied in terms of performance of perceptual tasks and has been found to impact the distribution of attention across the visual field (Elliott & Giesbrecht, 2010). As attention is integral to goal-directed movements and attentional load modulates visually distributed attention, it can be expected that overall task load would impact movement performance. The bulk of load studies have cognitive outcome measures and although there have been a few studies into task load and ambulation (Patel, Lamar & Bhatt, 2014; Nascimbeni, Minchillo, Salatino, Morabito & Ricci, 2015), the impact of load on fine motor movements still requires investigation. Here we use a dual task paradigm to investigate how cognitive load impacts the distribution of attention during a goal directed movement.

9.2.1. An Introduction to the Concept of Load and its Relationship to Attention

The term 'load' conceptualises an amount of resources that a given task engages given that the resource is finite. Cognitive load is an umbrella term referring to the load associated with all the cognitive (processing) resources available to an individual. Memory, perceptual and attentional load are portions of this cognitive resource pool. Key to understanding how load is thought about is the idea that processing resources have a maximum capacity that limits perception, brain activation and behavioural outcomes. As cognitive complexity (perceptual load, p-load) increases, task performance decreases (Plainis, Murray & Chauhan, 2001). This relationship is not unidirectional, as the visual information of the target is degraded the associated cognitive load of the task increases (Yu, Prasad, Mir, Thakor & Al-Nashash, 2015). Cognitive load has been found to impact more than basic visual tasks the interference produced by distractors is evident even with visually rich stimuli such as faces and environmental scenes (Minamoto, Shipstead, Osaka & Engle, 2015).

Perceptual load theory (PLT, Lavie, 1994) is currently the dominant theory addressing the incorporation of load into attention paradigms in the literature. PLT views perceptual load (p-load) as the factor which determines attentional deployment to the visual scene while performing a goal-directed task. This allows load to be viewed as a flexible contingency which allows for early or late selection based on the level of task difficulty. Difficult tasks have high p-loads which means there is a lot to process to accomplish the top-down task goal leaving few resources spare for processing non-attended stimuli allowing for early selection. Conversely if the task has a low p-load many non-target items would be processed and late selection would be employed (for reviews see Lavie, 1995; 2005; Lavie, Beck & Konstantinou, 2014).

The major difference between PLT and competing theories such as 'dilution theory' (Benoni & Tsal, 2013), is the definition of high and low load displays. Traditional PLT studies have used a single stimulus 'pop out' display for low-load and a target embedded in distractors for high-load displays. Proponents of dilution theory suggest this fundamental difference between displays may have a confounding influence. The suggestion is to keep the display consistent in terms of number of stimuli and define high/low load conditions as a function of the difference in levels of processing needed to differentiate the target from distractors (Benoni & Tsal, 2010).

As attentional allocation and vision are of importance to goal-directed movements and load has been found to impact both these mechanisms, one could surmise that load impacts aimed movements. As yet there have been no direct tests of these theories in the literature. Therefore this study assesses the impact of task load on the making of goal-directed movements.

9.2.2. Load, Visual Eccentricity and Dual-Task Paradigms

The spatial position of the target in relation to central vision, or target eccentricity is also an important factor for goal-directed movement. Eccentricity is a predominant aspect in many of the experimental designs used to study the impacts of task load (eg search task, flanker tasks and RSVP). Past findings suggest preferential allocation of attention to central vision when a stimulus is presented there (Wolfe, O'Neill & Bennett, 1998; Mackeben, 1990; Beck & Lavie, 2005; Handy, Soltani & Mangun, 2001), which is consistent with attentional load at fixation reducing cortical activation in areas associated with peripheral processing (Handy, Soltani & Mangun, 2001; Schwartz, Vuillemier, Hutton, Maravita, Dolan & Driver,

2005). These findings suggest the central/peripheral division of space is a suitable conceptualisation and an area of interest regarding studies of load.

The use of a dual-task interference paradigm is commonly used in studies of both attention and load. This paradigm is based on the principle of resource sharing, if dual-task conditions produce worse task performance than single-task conditions the conclusion that they share resources is reached. For example detrition of recognition performance (Landolt rings test) with eccentricity has been found, and can be more pronounced under dual-task conditions (Bondarko, Danilova, Solnushkin & Chikhman, 2014). High-load tasks at central vision have also been found to illicit worse peripheral performance than under low-load conditions (Chan & Courtney, 1993; Carmel, Saker, Rees & Lavie, 2007) again dual-task performance was worse than single-task performance (Handy et.al 2001; Schwartz et.al 2005). Nor is the peripheral task the only one impacted by dual-task conditions; studies have also shown degradation of performance for the central task as well (Chan and Courtney, 1993; Plainis et.al 2001; Pastukhov, Fischer & Braun, 2009; Long & Ma-Wyatt, 2014).

9.2.3. Load, Goal-Directed Movements and Movement Speed

The principle aim of this paper is to contribute to the sparse literature that directly assesses the influence of attentional load on goal-directed movement. In an investigation into load and eye movements, MacInnes and Hunt (2014) found load impacted the precision of the target localisation and eye movement to a remembered target. Chieffi, Iavarone, Viggiano, Monda and Carlomagno (2012) found that a line dissection reaching task was negatively impacted by flanking distractors. Furthermore in a study of goal-directed walking in a virtual reality environment, Kannape, Barre, Aminian and Blanke, (2014) found engaging in a task of high-load did not impact movement enactment but it did interfere with

walking speed. They also found high perceptual uncertainty in the non-walking task impaired motor awareness. This provides some evidence backing the assumption that as load impacts vision and attention, both important factors for movement generation and therefore is capable of impacting goal-directed movements.

The speed of the movement undertaken could also be pivotal to studies of goal-directed movement and load. Fast reaching speeds limit the time available to gather updating information (Saunders & Knill, 2003). 150ms is needed for the online updating system to process the relevant information, amend the original movement plan and start to adjust the movement (Kane, Wade & Ma-Wyatt, 2011). Fast movements place stress on the system because there is reduced time for online updating and may therefore magnify observable effects due to any experimental manipulation employed. It can therefore be argued that fast movement speeds act as a high-load situation (with increased task difficulty), conversely slow movement speeds would place the minimum load on the movement system. Another important aspect to consider is the impact that load may exert on the online updating system. Previous work has demonstrated that online updating can be impacted by attention during slow but not fast reaches. The impact of attention may not be consistent across feedforward and feedback processes, when producing fast movements attention has been found to impact the movement latency (ML) (which incorporates movement planning time) but not reach time (RT) (which has an updating component) (e.g. Liu, Chua & Enns, 2008; Long & Ma-Wyatt, 2014).

9.2.4. Study Design and Aims

The current study aims to examine the impact of attentional load on goal-directed movement along several different dimensions. A single-task / dual-task comparison will be

made on the performance of a centrally presented search task and a peripheral pointing task completed individually or at the same time. Low-load and high-load conditions will also be tested with the stimuli consistent with the distinctions used in studies of dilution theory enabling us to assess results which are consistent with with this theory. Furthermore although the search task is always presented in central vision, pointing targets can appear at one of two peripheral eccentricities. As acuity declines with eccentricity it may be expected to negatively impact localisation and therefore the reaches endpoint. However, exactly how localisation and enactment of goal-directed movement is affected by changing cognitive load has yet to be studied and one of the aims of this current study is to fill this gap. Fast and slow reach conditions will also be conducted partly to assess the viability of this manipulation in terms of impacting load, and partially to see any load effects on the reach time of the movement. We will also measure reach accuracy and precision and the movement time will be segmented into the pre-movement planning time (movement latency) and the time taken to complete the reach (reach time).

Fast and slow movement speeds different aspects of the goal-directed movement system. Fast movements place strain on the movement system amplifying responses to the experimental manipulations allowing investigation into aspects of automatic responses. However due to the brief duration of the movement limited online updating and correction to the initial movement plan is possible (Gordon, Ghilardi & Ghez, 1994). The use of slow reach conditions was designed to assess the impact attentional load manipulation may have on the updating of a movement. Because task difficulty can increase with movement speed (Fitts, 1954, Fitts Index of Difficulty), conducting fast and slow movement conditions allows a comparative analysis between movement's speeds and therefore the possibility of movement speed manipulating load can be investigated.

Due to the suitability of the high / low-load manipulation according to dilution theory and increased cognitive complexity producing poorer performance, we can expect performance on the baseline search task to be better under low load than high-load conditions. Given the general findings of dual-task decrement and the sharing of that decrement across tasks, it is expected that search task performance will be lower under dual-task conditions irrespective of the load of the search task. Similarly, a decrement in goal-directed movement performance is expected under dual-task conditions and this decrement will be more pronounced when the movement is coupled with high-load conditions as attention will be harnessed by the search at central vision. Based on past studies which have found the detrimental impact of load increases with eccentricity (Chan & Courtney, 1993; Carmel et.al, 2007; Bondarko et.al, 2014), we can predict movement endpoints to be least accurate when at a greater eccentricity and paired with the high-load search task. Although studies directly investigating the relationship between movement speed and task-load are scarce, the indirect links discussed earlier suggest that an exploratory investigation into how movement speed and load interact will provide further insight into how the senosirmotor system copes with varying task demands.

9.3. Method

9.3.1. Participants

Five participants (*N*=5; four females and one male), aged 23 to 42, participated in all experimental conditions after informed consent was obtained (in accordance with guidelines specified by the human ethics committee of Adelaide University). All were experienced psychophysical observers and right hand dominant as assessed by the Edinburgh Handedness Inventory (Veale, 2014). As the aim of the study was to measure normal visual and motor

responses, all participants had normal or corrected to normal vision and unimpeded arm movement. Conforming to traditional psychophysics methodology, statistical power was obtained via trial number rather than number of participants. Four of the five participants were naive to the aims of the study, the other was one of the authors. Participants were free to leave the study at any time without penalty and were offered feedback on completion of the study.

9.3.2. Materials

Custom software for the experiment and preliminary data analysis were written in Matlab using routines from the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The experimental conditions were displayed on a 17 inch ELO monitor which had a pressure sensitive layer applied to enable touchscreen capabilities. This allowed for the exact point of contact between the finger and the screen to be identified and sensitive time measures to be recorded. The screen ran at 1024 x 768 pixels and had a refresh rate of 60 Hz. The movement endpoint data were returned via the touchscreen. We then calculated accuracy and precision of the movement endpoints as reported previously (Long & Ma-Wyatt, 2015), accuracy being the difference between the target location and the touch location and precision the standard deviation of these data. Movement latency was calculated as the time between the pointing stimulus onscreen display and the onset of the reach (as indicated by the lifting of the finger from the mouse button in order to make the reach), and the reach time or the time between when the finger lifts from the mouse to start the movement to the end of the reach when the monitor is touched. Response to the search task was made using the keyboard and all data were analysed offline using Matlab and SPSS.

9.3.3. Procedure

Participants were seated in a darkened room to avoid ambient light impacting the processing of luminance from the screen, a stable 40cm between face and screen was obtained with use of a chin rest. The pointing stimulus was a high luminance dot 0.5^0 in size with a 43% Michelson contrast and was shown for 100ms. The pointing target could appear at any one of eight locations with equal probability, distributed in a ring shaped array and over two eccentricities, 8 and 4^0 from central fixation. Pointing stimulus target positions were 90^0 apart and could appear at locations the equivalent of 12, 3, 6 and 9 o'clock on a clockface (see figure 1).
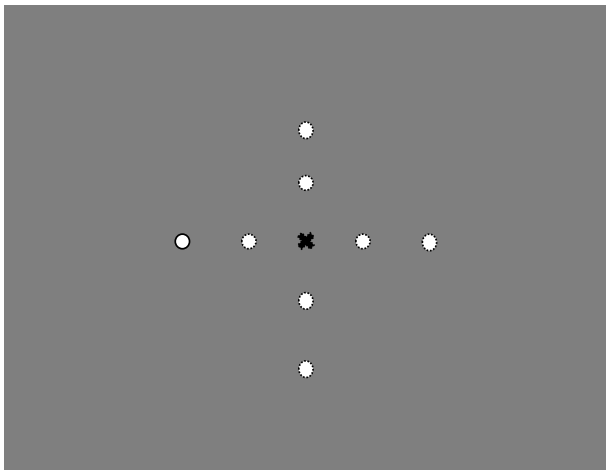
Figure 1 Array of possible pointing stimulus locations with four possible locations at both 4 and 8 degrees from central vision.

The pointing stimulus is expected to harness all available peripheral processing resources as high luminance has been found to 'capture' attention (Franconeri, Hollingworth & Simons, 2005) and the brief presentation time (100ms) ensures localisation was processed peripherally and prevents attentional shifts (Deubel, Schneider & Paprotta, 1998) that might otherwise confound the output. This type of circular display has been utilised in past studies (Ma-Wyatt & McKee, 2006; Song, Takahashi & McPeek, 2007; Long & Ma-Wyatt, 2014)

and it ensures the target coverage of the visual field is even and prevents left/right bias. It also conforms to Juola et al.'s (1991) study of attentional deployment across the visual field which found attention was distributed in rings around the central fixation point.

9.3.4. General Conditions

Participants were seated during the experiment and given instructions and practice trials before each condition during the study. They were offered further practice trials before commencement of data gathering to ensure the instructions were well understood and to negate any learning effects. At the beginning of each testing session a training condition was completed in the relevant movement speed for that block of trials (fast or slow speeds) this ensured participants were consistent in their understanding of what a baseline slow and fast reaching speed was. The program indicated its readiness to present the next trial when a small black cross appeared in the centre of the grey screen. Participants were instructed to depress the right side mouse key once they had seen the black cross and were ready to commence the trial. The mouse button was held down until a pointing response was made to the peripheral movement stimulus with the right index finger (the same digit as was used to make the pointing movement). The order of condition presentation was randomised for each individual participant with the data for each of the conditions being obtained in small blocks over several sittings. This counterbalanced any order or practice effects that may have been evident in the data set.

9.3.5. Conditions

This study employed a repeated measures design so every participant contributed to both the baseline and experimental data, essentially each individual provided their own

comparative baseline for each of the tasks. This allowed for comparative analysis between single-task (undivided attention) and dual-task (divided attention) performance for all outcome measures. The experiment in its entirety took five to six hours to complete but due to the possibility of motor fatigue or attentional wandering individual testing sessions lasted between 30 minutes and one hour. Each participant decided how long each individual session lasted. Participants were also offered a break between the condition blocks (each block contained 120 trials and took between 10 and 15 minutes depending on condition complexity).

9.3.6. Training in Reach Duration

As there was no guarantee that individual participants would share the same temporal definition of what constituted a 'fast' or 'slow' reach, a training condition was provided at the beginning of each testing session to ensure all observers had a similar foundation concept of the different reach times. The speed of the training block was dependent on the movement speed investigated in that session of data gathering, so if slow reach conditions were being tested the session started with slow reach training. The training conditions were similar procedurally. In both cases, the initial grey screen with central fixation cross was shown, and participants started the trial by button press at which point the fixation cross was extinguished, and then a target (a high luminance white dot was shown at one of eight possible locations. Participants were instructed to hit the white dot. Before commencement of the 50 trial training block participants were informed of the movement speed to be made (fast or slow). At the end of each trial feedback was given, in the fast reach condition a reach greater than 0.5sec resulted in 'Too Slow' appearing onscreen. In the slow reach condition if the reach was quicker than 1.5sec the message 'Too Fast' appeared. In both training conditions, if the reach was within these parameters no feedback was given and readiness for

the next trial was presented. The movement time on which feedback was based consisted of the time between stimulus presentation and endpoint touch.

9.3.7. Search Task

In order to be certain the search task would continue past the end of the reach for both fast and slow movements a slightly different length search task were presented for fast (15 letters) and slow (20 letters) movement trials. In the condition where cessation of the search task coincided with the presentation of the peripheral target a shorter search was employed (6 letters). Pilot data indicated the length of the search task impacted the outcome so each length of letter string used in dual-task conditions required its own baseline condition. This resulted in six baseline search task conditions, three high-load searches and three low-load searches of 6, 15 and 20 letters. Under high-load conditions the letters shown were a randomised selection of 10 letters, from 'A' to 'J' (e.g. C H A E H J). The low-load search was a string of letters totally constructed of 'H' and 'O' (e.g. O O H O H O) which were once again presented in random order.

The load conditions were consistent with several suggested experimental manipulations employed to vary load. The high-load search had many possible items while the low-load condition had only two, this changed the content of homogeneous non-target items thus impacting on task difficulty (Song et.al 2007; Stolte, Bahrami & Lavie, 2014) and changing task difficulty modulates load (Lavie et.al 2014). The tasks also differ in processing requirements, target identification in the high-load condition requires identification of several, varied features while the difference between items in the low-load condition differed along basic dimensions (Treisman FIT, 1964), this manipulation also results in predictable load fluctuations (Lavie, 1995).

As with all experimental trials participants were first presented with a grey screen which had a spatial fixation dot in the centre of the screen. Participants indicated the trial should commence by pressing the right mouse key which triggered the presentation of the search items presented in a serial manner where the central fixation point had been. Serial search presentation allows for the search process of feature binding which requires serial target presentation and is necessary for this type of search (Wolfe, 2003). Each item in the letter string was presented for 16ms with a 16ms gap between items to negate backwards masking. After the completion of each letter string participants were asked 'How many times did you see 'H'? and responded using the number array on the keyboard. Observers were aware before participation of the target letter identity and the letter 'H' remained the target in all trials. For all baseline search conditions 160 trials per participant were collected resulting in a total of 800 data points for each condition.

9.3.8. Baseline Goal-Directed Movement Conditions

There were two baseline pointing conditions (BP) where the peripheral pointing task was completed minus the presence of a central search presentation creating single-task (undivided attention) conditions. The only difference between the two BP conditions was the speed of the pointing movement to be made. Participants were asked to make either a slow or a fast pointing movement to the target location. They were asked to make this movement as soon as they perceived the pointing targets appearance (see figure 2). Movement target locations were randomised and displayed with equal probability. The short onscreen duration of the pointing target (100ms) prohibited attentional shifts (Baldauf & Deubel, 2008). This allowed these data to reflect the dispersion of attentional deployment generated by task conditions. The brief duration also prevented foveation of the target and movement of the stimulus's retinal position and ensured that the stimulus was localised using peripheral vision

(Desmurget, Pelisson, Rossetti & Prablanc, 1998). Each participant contributed 25 data points at each of the eight possible locations for both BP conditions. This resulted in each participant contributing 2000 trials and a total of 1000 trials for each condition.
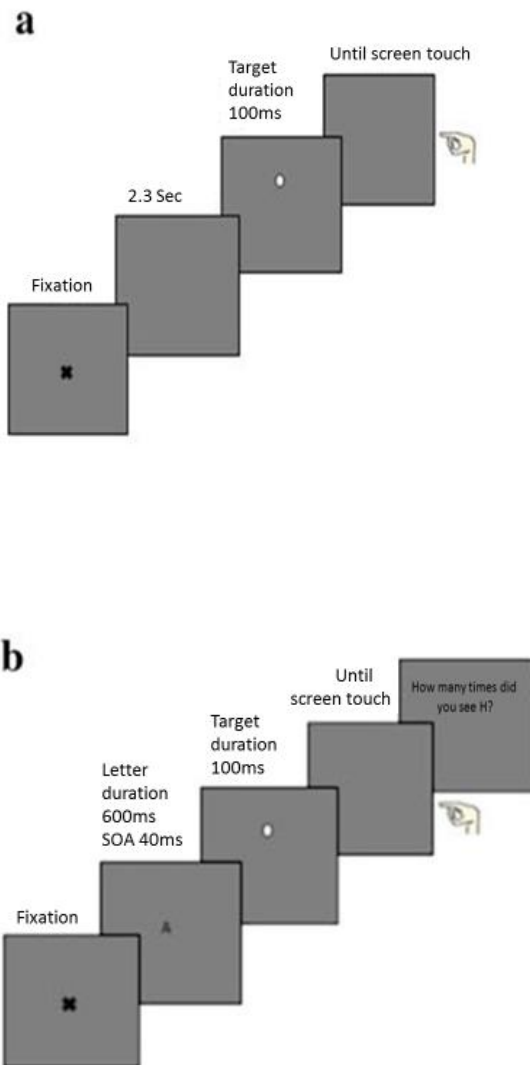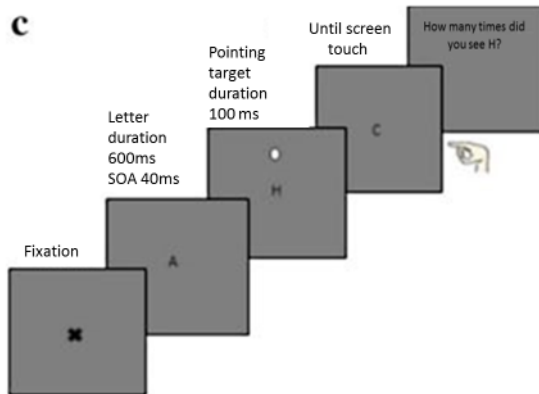
Figure 2 Sequence of events in the baseline goal-directed movement condition (BP); the sequence of events in the Part Reach (PR) condition, when the search task concludes concurrently with the presentation of the pointing stimulus; and the sequence of events in the Whole Reach (WR) condition, when the search task continues throughout the reach.

9.3.9. Dual-Task Conditions

The dual-task conditions consisted of a central search task and a peripheral goal-directed pointing movement performed at the same time and requiring attentional division. Each trial started with presentation of the grey screen with a central fixation point indicated by a black dot. Participants started the trial by pressing the right mouse key with their right index finger, they left this pressed down until the finger was lifted to make a movement response. Commencement of the task erased the fixation dot and the presentation of the serial search task began in that same spatial location. The search task began before the movement whose peripheral target is presented along with the sixth letter of the search task. In one condition the search task ceases at this point (PR), in the other it continues until after reach

completion (WR) (see figure 2). The pointing target appears for 100ms in one of eight peripheral locations and at an eccentricity of 4^0 or 8^0. Participants were asked to make a pointing movement to the location of the target as soon as it was presented. At the end of the trial observers were asked to indicate how many H's they had seen in that string using the numbers on the keyboard.

There were a total of eight dual-task conditions tested. Tasks differed based on when the search task stopped in relation to the movement, either as movement target localisation was taking place (PR) or after the reach was complete (WR). Each of these conditions was paired with either a high-load or low-load search task. The final manipulation related to the temporal characteristics of the reach and consisted of fast (less than 0.5 of a second) and slow (greater than 1.5 seconds) movement conditions. As with the BP condition, each observer produced 200 trials per condition resulting in a total of 1000 trials available for each of the dual-task conditions. Cessation of the search task during localisation (PR) adds a further dimension to our investigation of attention as it enables us to compare conditions of ongoing central search during the reach and a situation where attentional resources are free to disengage and redistribute. As attention facilitates goal-directed movements, no longer having to divide attention may improve movement performance as now it has the entire attentional resource. However, this is not necessarily the case and studies have reported performance derogation directly following task switching which is generally known as 'switch costs' (Monsell, 2003). Traditionally the study of switch costs have related to a switching of a complete task rather than just part of a dual-task. Therefore this condition represented a way to modulate attention rather than an investigation into switch costs.

9.3.10. Outcome Measures

Search task performance resulted in three variables being recorded, the observer's response to how many 'H' they saw, the actual number of H's in the letter string and the identity and order of the letter string presented in that trial. Actual number of H's and the participant responses were used to calculate the percentage of correct responses for each condition during data cleaning processes. The letter strings were not used in analysis but were obtained in order to rule out search task effects being due to attentional blink (AB). This was achieved by comparing the number of incorrect trials which held sequentially presented target letters and those that did not using a *t*-test to check for differences. If a significantly greater number of trials held sequential presentations of the target, AB may have been indicated and further analysis would be needed to ascertain if a longer interval between letter presentations was required.

Accuracy of reach endpoints was calculated by measuring the Euclidean distance between exact stimulus position and the touch location of the pointing movement. Precision, or variability of the touch locations distributed around the stimulus position, was calculated as the standard deviation of the accuracy measures (Long & Ma-Wyatt, 2014).

The overall reach time was segmented into two variables, movement latency and reach time. Movement latency (ML) was measured as the time between pointing stimulus presentation and the finger movement initiation reflecting pre-movement planning time. Reach time was the time between the key release and when the finger touched the monitor. Readiness to begin each trial was indicated by pressing the right mouse key and observers were instructed to continue holding it down until they saw the pointing stimulus and responded by pointing with the same finger that was holding down the key.

9.4. Results

Due to the large number of variables involved the analysis was conducted and reported in three stages. By approaching the results in stages provided structure and clarity to a complicated and large data set. Additionally a system of shortening variable labels was devised to simplify and reduce reporting repetition. Experimental conditions were referred to as BP, PR and WR. BP indicated the baseline pointing condition. PR or the part-reach condition is where the alphanumeric search task completion occurs simultaneous with pointing target appearance. And WR signifies the whole-reach condition where the central search task continued throughout the reach. The two other variable conditions specified in the shortened variable labels appearing after the experimental condition are the load condition, 'L' for low-load and 'H' for high-load, and movement speed 'F' for fast goal-directed movements and 'S' for slow movement latencies. For example, PR.L.F. would indicate the variable being investigated was the Part-Reach condition with a search task that was low-load and performed with a fast movement speed, individual data was combined across participants for analysis.

9.4.1. Phase 1 of the Analysis: search task performance

Search task responses were analysed for correct identification of the number of 'H's presented in the central search task. When producing the final search results, data were binned in groups of 10 by trial number, assessed for percentage of correct responses then pooled across observers and pairwise t-tests employed to test comparisons. The traditional significance criteria of $p=.05$ was reduced to $p=.016$ to account for multiple testing.

A series of t-tests were performed using only the single-task baseline search task conditions to investigate how performance on letter strings of the same length were impacted

by attentional load conditions. The difference between baseline high and low load for searches of 15 letters was significant ($t(38)=4.1$, *SEM*=2.28, $p<.005$), as was the difference on searches 20 letters in length ($t(31)=3.65$, *SEM*=2.21, $p<.005$). In both instances, there were more correct responses under low-load conditions than high-load. The searches 6 letters in length were not different dependant on load condition ($t(38)=.52$, SEM=2.22, $p=.61$) (see figure 3).

This analysis directly compared load conditions keeping all other factors constant to test the experimental load manipulation. There were no instances of high-load outperforming low-load and two of the three comparisons found low-load significantly outperformed high-load conditions. Based on this it was concluded that the load manipulation was successful and task difficulty was modulated impacting the cognitive load associated with the task. The results suggest the length of the serial search task can also operate to modulate search performance as there was no difference between low and high load searches for strings six letters in length. This suggests that if the search doesn't exceed capacity limitations, then a load manipulation has little effect.
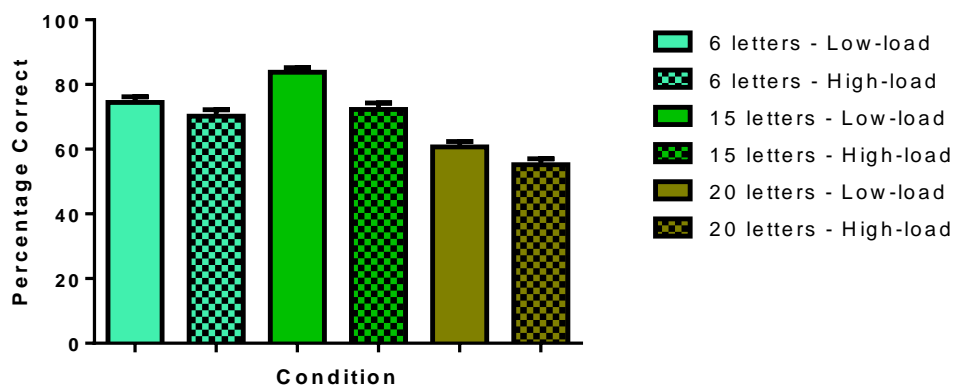
Figure 3 Comparative analysis of the impact of load on letters strings of the same length under single-task conditions. Error bars represent 1 SEM.

The next analysis of search task responses focused on the difference between the performances of high and low search tasks when completed in dual-task trials that required both search and pointing movement performance in the same trial. This analysis was conducted to ascertain if the pattern of results found in single-task conditions was replicated for dual-task conditions as it focused on the impact of attentional load. Movement speed was held constant.

A statistically significant difference between high and low load was observed for search task performance when the letter string was 15 letters long (WR.L.F. & WR.H.F.) ($t(44)=4.81$, *SEM*=1.98, $p<.005$) and with letter strings 20 letters in length (WR.L.S. & WR.H.S.) ($t(49)=5.29$, *SEM*=2.26, $p<.005$). In the part reach condition (P.R.), the shorter search tasks (6 letters long) did not show differences in the impact of load (fast reach; $t(43)=.7$, SEM=2.49, $p=.49$; slow reach; $t(46)=1.79$, SEM=2.27, $p=.08$) under dual-task conditions (see figure 4).

Under dual-task conditions the search task was impacted only in the longer search tasks that continued throughout the reach (WR) regardless of reach speed but was not impacted in disengaged reaches (PR) that had shorter search tasks. Once again search task performance was only impacted by load in longer letter strings leaving searches six letters long unaffected.
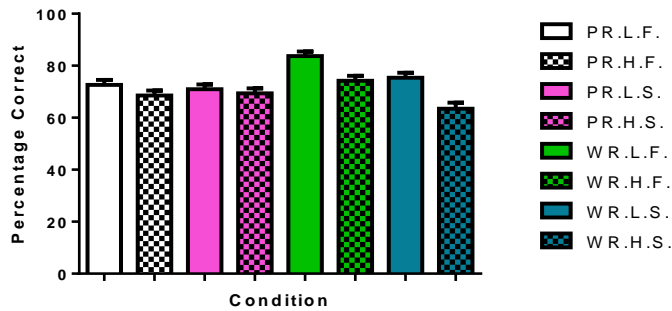
Figure 4 Comparisons of high and low search task performance for search tasks of the same length under dual-task conditions (search performance when conducting a reach in the same trial). Error bars represent 1 SEM. Trials were either under part reach (PR) or whole reach (WR) conditions, the searches were either low-load (L) or high-load (H), and accompanied by either a fast (F) or slow (S) reaching movement.

To provide further evidence regarding attentional distribution between central and peripheral visual regions under load, direct comparisons between single and dual-task searches keeping all other factors constant were conducted. The only significant difference found between single-task and dual-task search performance was for searches 20 letters long (WR condition with slow movement speed) but this difference was found for low (WR.L.S.) ($t(39)=5.56$, *SEM*=2.16, $p<.005$) and high (WR.H.S.) ($t(39)=4.86$, *SEM*=2.45, $p<.005$) load comparisons. No other comparisons between baseline and dual-task search performance met the significance criteria of 0.016, adjusted from 0.05 to correct for multiple testing.

The general lack of difference between dual-task search performance and the corresponding single-task baseline adds further evidence of an attentional bias towards the central task. Contrasting with the earlier finding of no difference between load conditions for short search tasks (representing a 'floor' to capacity limits) search task performance was negatively impacted by dual-task conditions only for the W.R. conditions (searches twenty letters long irrespective of load condition). This may indicate a 'ceiling' effect where the accumulated task load is so high even the central attentional bias is not able to compensate leading to search task performance degradation.

In order to have a complete picture when assessing the impact of pointing target eccentricity on resource distribution across the visual field, individual t-tests were performed for PR and WR dual-task conditions assessing the percentage of correct search responses obtained when accompanied by 4º or 8º pointing target. Search task performance was found to be unaffected by the eccentricity of the concurrently performed reaching movement (t(39)1.28, SEM=.88, p=.21).

9.4.2. Phase 2 of the Analysis: Comparison of high and low load across all experimental conditions while reaching slowly

The load manipulation was successful in altering search performance on different lengths of letter strings. In this section, we report analyses designed to test how these load manipulations affected the performance of a goal directed movement under dual-task conditions.

In order to assess the impact of experimental task (BP, PR & WR) and load condition, a mixed models analysis was conducted on reaching outcome measures holding movement speed constant. A LMM analysis investigating movement accuracy when moving slowly assessed the fixed factors of high and low attentional load, and the experimental conditions (BP, PR and WR) over both eccentricities. Participant identification was considered a random factor to account for individual differences. This analysis found a significant main effect for condition (F(3520,4)=10.52, p<.005), eccentricity (F(3519,1)=25.56, p<.005) and the interaction effect (F(3519,4)=3.07, p=.015) was significant.

Slow reaching when paired with low-load search conditions produced accuracy that was significantly different between BP.S. and PR.L.S. ($Mdiff$(3520)=.07, SEM=.02, p=.001) but not BP.S. and WR.L.S. ($Mdiff$(2194)=.03, SEM=.02, p=.312). PR.L.S. and WR.L.S. also had significantly different accuracy performances ($Mdiff$(0.018)=.11, SEM=.02, p<.005). The

PR.L.S. conditions resulted in the least accurate movement endpoints ($M(5)$=.48, SEM=.03) (see figure 6). Slow reaching when paired with high-load search conditions produced accuracy that was not significantly different from BP.S. for either the PR.H.S. ($Mdiff$(2194)=.03, SEM=.02, p=.312) or WR.H.S. ($Mdiff$(2204)=.001, SEM=.02, p=1) conditions, nor were they different from each other. When comparing pointing accuracy between high and low-load search task conditions of the same length, load did not impact pointing accuracy under PR (PR.L.S. vs PR.H.S. ($Mdiff$(2193)=.04, SEM=.02, p=.163)) or WR (WR.L.S. vs WR.H.S. ($Mdiff$(2201)=.04, SEM=,02, p=.13)) conditions.

Eccentricity also impacted accuracy when reaching slowly. Pointing targets at 8° ($M(5)$=0.46, SEM=0.02) being less accurate than 4° ($M(5)$=0.4, SEM=0.02). Pointing precision was not impacted by experimental condition (F(110,2)=.27, SEM=.015, p=.76).

Generally, slow reaching movements did not deviate from baseline levels on either endpoint measure (accuracy or precision) due to the impact of central search task load. However, experimental condition effects were evident. Under low-load conditions, PR was significantly less accurate than both BP and WR conditions reflecting an underlying switch cost for accuracy but not precision. It's possible that the lack of dual-task deviation from single-task performance levels reflects a lack of stress placed upon the capacity of the pointing system. Consistent with previous findings, there was a reduction in accuracy at greater eccentricities.
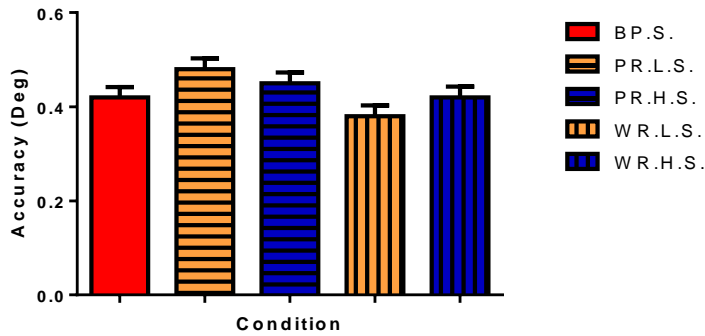
Figure 5 Accuracy of pointing movements when reaching slowly under low and high load conditions. Data are the mean across all participants and error bars represent 1 SEM. Trials were either under baseline pointing (BP), part reach (PR) or whole reach (WR) conditions, and the searches were either low-load (L) or high-load (H), and accompanied by a slow (S) reaching movement.

In order to get a fuller picture of the impact of the experimental (BP, PR and WR) variables on pointing, the timing of the movements was also recorded. The overall movement time was segmented to allow investigation into how experimental conditions impact different movement stages with their individual functions, the pre-movement planning stage (ML) and the time the arm was in motion (Reach Time).

The LMM analysis had the same factors as the previous analysis, fixed factors were BP, PR and WR; in both low and high-load conditions over both eccentricities and participant ID reflecting individual differences was considered a random factor. ML showed a significant main effect for condition ($F(3519,4)=12.63$, $p<.005$) and an interaction effect ($F(3519,4)=3.11$, $p=.015$) but eccentricity was not significant ($p=.024$ which was not significant at the .016 criteria set to account for multiple testing).

Baseline ML (BP.S.) performance only differed from WR.L.S. ($Mdiff(3519)=0.13$, SEM=.02, $p<.005$), not PR.L.S ($Mdiff(2268)=.04$, SEM=.03, $p=.487$) conditions. BP.S. had a faster ML than WRL.S ($Mdiff(2268)=.13$, SEM=.03, $p<.001$). There was a significant difference between PR.L.S. and WR.L.S. conditions ($Mdiff(3519)=0.1$, $SEM=.02$, $p<.005$);

WR.L.S. had a longer ML than PR.L.S. (see figure 6). With high-load search conditions, ML for PR.H.S. and WR.H.S. conditions did not differ from baseline (BP.S.) or each other.

ML was impacted by the load condition of the search under PR for 6 letter conditions (*Mdiff*(3519)=0.1, *SEM*=.02, *p*<.005); PR.L.S. having a shorter ML than PR.H.S. Load also impacted ML under WR (20 letter) conditions (*Mdiff*(3519)=0.13, *SEM*=.02, *p*<.005) with high-load (WR.H.S.) conditions faster than low-load (WR.L.S.) (see figure 6).

The reach times under slow reach conditions had a significant main effect for condition (*F*(3519,4)=104.06, *p*<.005) but not for eccentricity (*F*(2268,1)=42, SEM=.12, *p*=.518) and the interaction effect was not significant (*F*(2268,2)=.04, SEM=.12, *p*=.958). PR's for all conditions were significantly different to each other apart from the high and low-load WR conditions (WR.L.S. vs WR.H.S.) where no difference was found (see figure 6).

The switch costs evident in the accuracy data were not reflected in the ML. The ML paired with a low-load search that continued throughout the reach (WR.L.S.) was significantly longer than PR.L.S. and BP.S. latencies. This contrasts with reaches paired with high-load searches which did not deviate from baseline. Reach time was different from baseline in each of the dual-task conditions. Interestingly, when completing a dual task movement latencies generally increased while reach times generally decreased relative to baseline.

a)   Movement Latency   b) Reach Time
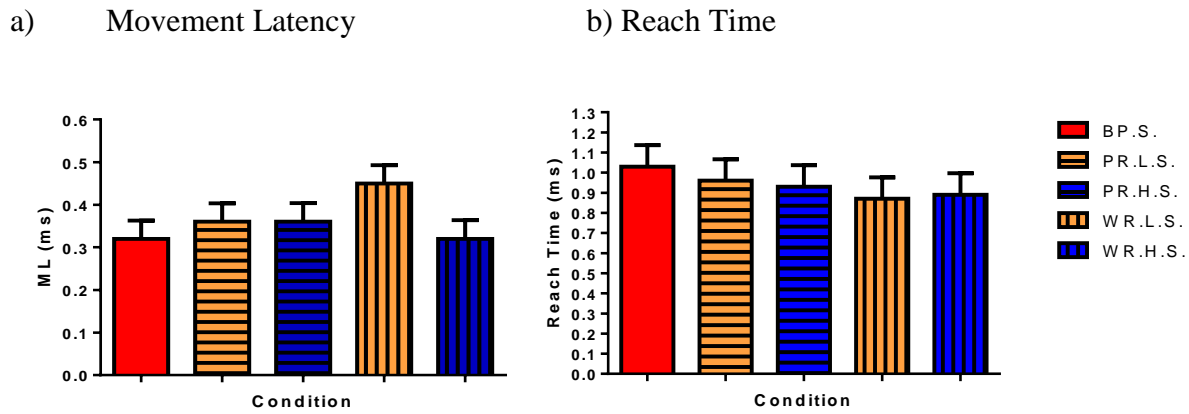
Figure 6 Movement Latency and Reach Time under Slow Reach Conditions. Data are the mean across all participants and error bars represent 1 SEM. Trials were either under baseline pointing (BP), part reach (PR) or whole reach (WR) conditions, the searches were either low-load (L) or high-load (H), and accompanied by a slow (S) reaching movement.

9.4.3. Phase 3 of the Analysis; Comparison of high and low load across all experimental conditions while fast reaching

As movement speed was held constant in the previous analysis assessing the impact of experimental task (BP, PR & WR) and load condition, a second analysis which only contained trials from fast reaching conditions was conducted. The traditional significance criteria of $p=.05$ was reduced to $p=.016$ to account for multiple testing. LMM analysis of fast reaching movements found accuracy had a significant main effect for condition ($F(3401,4)=8.05$, $p<.005$) and eccentricity ($F(3399,1)=40.78$, $p<.005$) but no interaction effect ($F(3399,4)=1.99$, SEM$=.04$, $p=.094$).

Pairwise comparisons of single and dual-task conditions found movement accuracy paired with low-load conditions displayed significantly different performances between BP.F. and both PR.L.F. accuracy ($Mdiff(3402)=0.08$, $SEM=.02$, $p=.004$) and WR.L.F. accuracy ($Mdiff(3402)=0.09$, $SEM=.02$, $p<.005$). However PR.L.F. and WR.L.F. did not differ from

142

each other. Single-task BP.F. pointing was less accurate than either dual-task conditions (PR.L.F. & WR.L.F.) (see figure 7).

Pairwise comparisons of single and dual-task conditions found movement accuracy paired with high-load conditions displayed a significant difference between BP.F. and PR.H.F. (*Mdiff*(3401)=0.11, *SEM*=.02, *p*<.005) but not BP.F. and WR.H.F. conditions. Difference between PR.H.F. and WR.H.F. failed to meet significance criteria once adjusted for multiple testing. Single-task baseline performance for BP.F was less accurate than PR.H.F.

When holding experimental condition constant (search task length), PR low and high-load conditions did not differ significantly in accuracy (PR.L.F. vs PR.H.F.) (*Mdiff*(3399).03, SEM=.023, *p*=1), nor did WR high and low load conditions (WR.L.F. vs WR.H.F.) (*Mdiff*(3399).06, SEM=.023, *p*=.09).

The main effect for eccentricity was significant with 8^0 (*M*(4)=0.63, *SEM*=.03) less accurate than 4^0 (*M*(4)=0.54, *SEM*=.03). No precision effects for fast reaching movements in either load condition were found.

There is a pattern of dual-task facilitation of accuracy with only one condition not exhibiting greater accuracy than baseline. Only the movement paired with a high-load search which continued throughout the reach was no different from baseline levels. This condition (WR.H.F.) was not facilitated by the allocation of attention to the visual field prior to the presentation of the pointing target. Once again there was an eccentricity effect with pointing to greater eccentricities associated with less accurate endpoints.
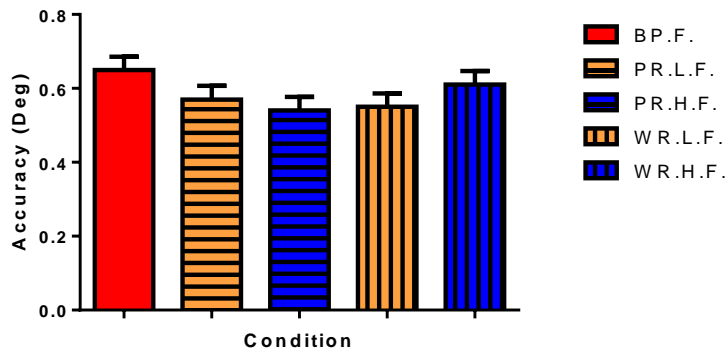
Figure 7 Accuracy during Fast Reach Conditions. Data are the mean across all participants and error bars represent 1 SEM. Trials were either under baseline pointing (BP), part reach (PR) or whole reach (WR) conditions, the searches were either low-load (L) or high-load (H), and accompanied by a fast (F) reaching movement.

As with slow reach conditions, fast reach movement times were segmented into movement latency and reach time for analysis. LMM analysis was conducted on the fixed factors of experimental condition (BP, PR and WR), high and low load and eccentricity with a random factor of participant. ML results showed a significant main effect for condition (F(3399,4)=38.43, p<.005) but not for eccentricity or an interaction effect.

With low-load search conditions ML, BP.F. was significantly different from both PR.L.F. (*Mdiff*(3399)=0.06, *SEM*=.01, p<.005) and WR.L.F. (*Mdiff*(3399)=0.04, *SEM*=.004, p<.005) conditions, BP.F. had a faster ML than both PR.L.F. and WR.L.F. (see figure 8). The two dual-task conditions were also significantly different to each other (*Mdiff*(3399)=0.02, *SEM*=.01, p<.005), with PR.L.F. having a longer ML than WR.L.F.

With high-load search conditions, ML for BP.F. was significantly different to both PR.H.F. (*Mdiff*(3399)=0.02, *SEM*=.01, p<.005), and WR.H.F. (*Mdiff*(3399)=0.03, *SEM*=.01, p<.005), but dual-task conditions (PR.H.F. & WR.H.F.) were not different from each other.

Part-Reach high and low-load (PR.H.F. & PR.L.F.) were significantly different from each other (*Mdiff*(3399)=0.03, *SEM*=.01, p<.005) suggesting there was an impact of search

task load on movement ML. However, WR high and low–load (WR.H.F. & WR.L.F.) did not have ML's significantly different from each other.

Reach Time results showed a main effect for condition (indicating a significant difference was to be found between the BP, PR and WR experimental conditions) (F(3399,4)=32.59, p<.005) but not for eccentricity (F(3399, 1)=1.2, SEM=.02, p=.273) or interaction effects (F(3399,4)=1.85, SEM=.02, p=.16).

When fast reaching and paired with low-load search conditions, reach time for PR.L.F. differed from BP.F ($Mdiff$(3399)=0.02, SEM=.002, p<.005) but WR.L.F. did not, the dual-task conditions (PR.L.F. & WR.L.F.) did differ from each other ($Mdiff$(3399)=0.02, SEM=.002, p<.005). Baseline (BP.F.) reach time was longer than PR.L.F. and WR.L.F. (see figure 8).

Fast reaching paired with high-load search conditions resulted in movement Reach Time differing between baseline (BP.F) and PR.H.F. performance ($Mdiff$(3399)=0.01, SEM=.002, p<.005) but not WR.H.F. conditions. The two dual-task conditions PR.H.F. and WR.H.F. were significantly different from each other ($Mdiff$(3399)=0.01, SEM=.002, p=.003).

When holding experimental condition (search task length) constant, PR low compared to high-load (PR.L.F. vs PR.H.F.) conditions did differ significantly in ML ($Mdiff$(3399)=0.02, SEM=.002, p<.005), but WR high and low-load (WR.L.F. vs WR.H.F.) conditions did not.

Unlike the previous slow reach analysis, ML was greatly impacted by experimental condition when reaching fast. BP had a significantly shorter ML than any of the dual-task conditions. Switch costs were evident for ML when paired with a low-load search as the PR condition was significantly longer than WR and high-load searches also impacted ML for PR but not WR conditions. Reach times were significantly shorter than baseline for both PR

conditions but not for WR high-load. The shortest reach times were found for the PR conditions suggesting disengagement has a facilitating effect on this outcome measure.

a) Movement Latency   b) Reach Time
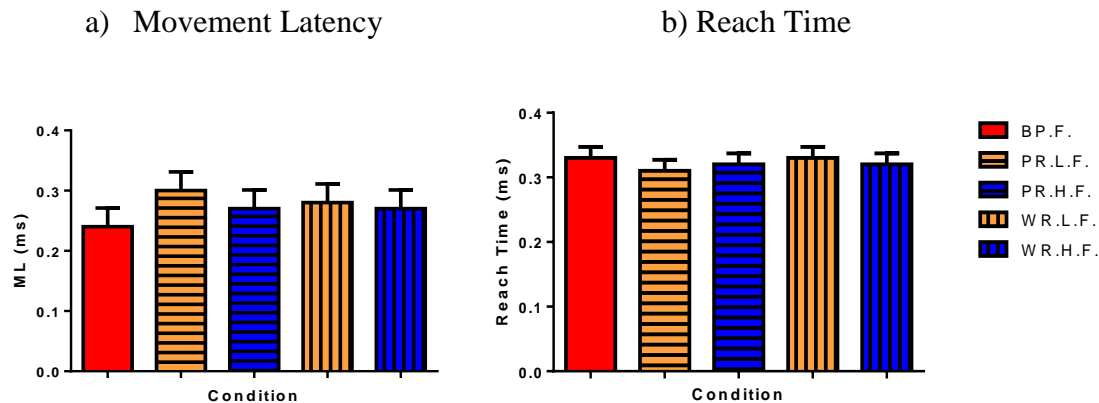
Figure 8 ML and Reach Time for Fast Goal-Directed Movements. Data are the mean across all participants and error bars represent 1 SEM. Trials were either under baseline pointing (BP), part reach (PR) or whole reach (WR) conditions, the searches were either low-load (L) or high-load (H), and accompanied by a fast (F) reaching movement.

9.4.4. Phase 4 of the Analysis; comparison of goal-directed movement speed across all experimental conditions paired with low-load searches

The previous results suggest that there are different patterns of results for fast and slow reaches. To understand precisely what is happening in relation to movement speed effects, an analysis directly assessing the impact of speed on the goal-directed movement system was conducted, holding load constant.

LMM analysis of reaching movements with low-load searches found accuracy had a significant main effect for condition (BP, PR & WR) ($F(4420,5)=50.91$, $p<.005$), eccentricity ($F(4418,1)=28.58$, $p<.005$) and interaction effect ($F(4418,5)=3.23$, $p=.006$).

The baseline conditions of fast and slow reaches (BP.S. and BP.F.) produced significantly different accuracy performances ($Mdiff(4422)=0.23$, $SEM=.02$, $p<.005$), with fast pointing conditions producing less accurate endpoints than slow (see figure 9).

Comparative analysis found PR (PR.L.F. and PR.L.S.) conditions differed dependant on movement speed condition ($Mdiff(4421)=0.08$, $SEM=.02$, $p=.005$), again with slow movement's corresponding to greater movement accuracy than fast movements. Fast and slow movements under WR conditions (WR.L.S. and WR.L.F.) were also significantly different ($Mdiff(4419)=0.17$, $SEM=.02$, $p<.005$) and slow movements were found to correspond to more accurate pointing than fast ones. Movement speed was found to have no significant impact on movement endpoint precision.

There was a consistent decrement in accuracy for fast compared to slow movement times (paired with low-load searches). This pattern of results supports the idea that moving fast placed stress on the movement system (in essence increasing task load), thereby amplifying differences due to experimental effect. Were this to be completely a reflection of the speed/accuracy tradeoff (Fitts' Law) then conditions would differ only on the speed variable (fast or slow) but attentional division (single baseline/dual-task conditions) would have no impact. Slow movements were found to be more accurate than fast conforming to a speed/accuracy tradeoff, however, there was also a consistent significant main effect for condition (BP, PR & WR). As the attentional division required for dual-task performance impacted pointing accuracy along with movement times results suggest a speed/accuracy tradeoff is not the isolated cause of the effects.
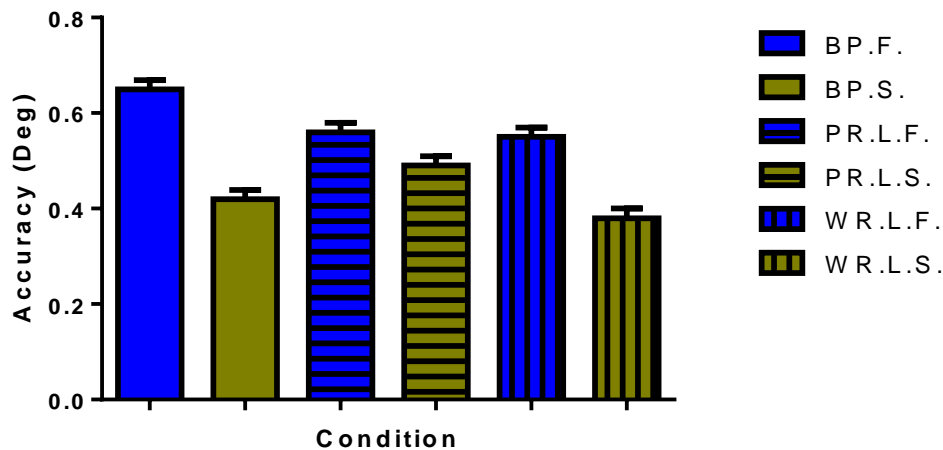
Figure 9 Accuracy for Goal-Directed Movements paired with a Low-Load Search Task. Data are the mean across all participants and error bars represent 1 SEM. Trials were either under baseline pointing (BP), part reach (PR) or whole reach (WR) conditions, the searches were low-load (L), and accompanied by either a fast (F) or slow (S) reaching movement.

As with previous analyses, movement outcome measures assessed included the two temporal measures as well as endpoint measures. Movement latency (ML) had a significant main effect for condition (BP, PR, WR) ($F(4419,5)=27.53$, $p<.005$) but not for eccentricity (once adjusted for multiple comparisons), the interaction effect was also significant ($F(4418,5)=3.53$, $p=.003$).

Baseline fast and slow reaches (BP.S. vs BP.F.) had significantly different movement latencies ($Mdiff(4419)=0.08$, $SEM=.02$, $p<.005$), BP.S. had a longer ML than BP.F. (see figure 11). There was no difference between PR.L.F. and PR.L.S. conditions for ML. The WR fast and slow reach conditions (WR.L.S vs WR.L.F.) were significantly different from each other ($Mdiff(4418)=0.16$, $SEM=.02$, $p<.005$) with slow reach conditions producing slower ML than was found with fast reaches.

The results showed slow reach times were paired with longer ML, this reflects more time devoted to pre-movement planning. This finding combined with a longer reach time allowing for more online updating accounts for the high levels of accuracy for slow movements found in the previous analysis. As the fast/slow experimental manipulation was

148

functionally a change in reach time, the results supported the basic experimental premise that slow reach conditions had longer reach times than fast reach (see figure 10).

a) Movement Latency   b) Reach Time
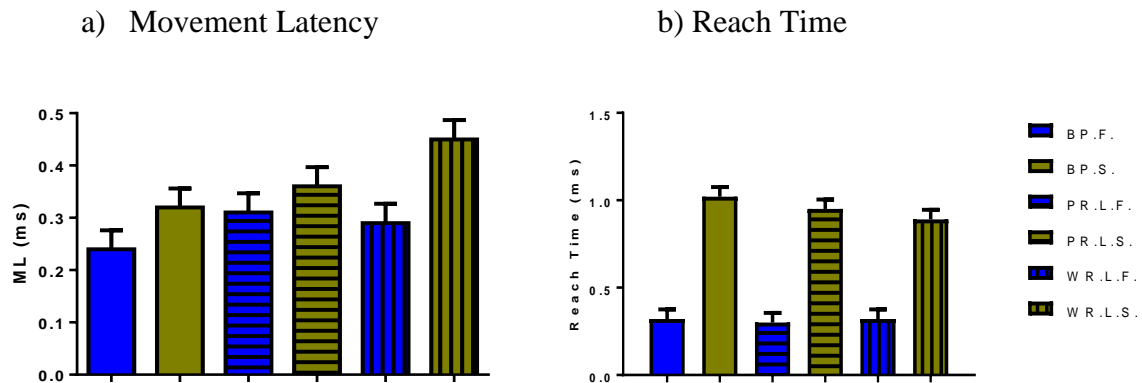
Figure 10 Movement latency and reach time under low-load conditions search task. Data are the mean across all participants and error bars represent 1 SEM. Trials were either under baseline pointing (BP), part reach (PR) or whole reach (WR) conditions, the searches were low-load (L), and accompanied by either a fast (F) or slow (S) reaching movement.

9.4.5. Phase 5 of the Analysis; comparison of goal-directed movement speed across all experimental conditions paired with high-load searches

To complement the previous analysis conducted on low-load conditions, a LMM analysis was conducted to assess the impact of movement speed (fast or slow) upon experimental condition (BP, PR and WR) accounting for the eccentricity of the pointing target (4° or 8° from central vision), and while engaged in high-load searches. Results found accuracy had a significant main effect for condition ($F(4185,5)=47.47$, $p<.005$) and eccentricity ($F(4183,1)=29.66$, $p<.005$) along with an interaction effect ($F(4183,5)=2.79$, $p=.016$).

Because BP conditions were performed without a search task component they remain the same in both sections (low and high load) of phase three's analysis. As previously mentioned, there was a significant difference between fast and slow baseline accuracy (BP.S. vs BP.F.), with slow movements being more accurate than fast ones (see figure 11). Fast PR

conditions also produced different accuracy performance in fast and slow conditions (PR.H.F. vs PR.H.S.) (*Mdiff*(4184)=0.08, *SEM*=.02, *p*=.006) with slow movements once again the most accurate. WR accuracy conditions were also impacted by movement speed (WR.H.F. vs WR.H.S.) (*Mdiff*(4184)=0.19, *SEM*=.02, *p*<.005) and slow reach conditions being once again more accurate than fast. Movement speed (fast or slow) had no impact on pointing precision. Consistent with the previous findings, greater accuracy was found for slow movements regardless of the experimental condition (BP, PR or WR) of the comparison.

Figure 11 Accuracy under high-load conditions search task. Data are the mean across all participants and error bars represent 1 SEM. Trials were either under baseline pointing (BP), part reach (PR) or whole reach (WR) conditions, the searches were high-load (H), and accompanied by either a fast (F) or slow (S) reaching movement.

The final analysis involved movement times associated with fast and slow reaches paired with high-load searches. LMM analysis was used to test if movement latencies and reach times in the high load conditions were significantly affected by movement speed condition. Therefore, the LMM model had movement speed (slow or fast), experimental condition (BP, PR and WR) and eccentricity (4^0 and 8^0) as fixed effects and participant identification as a random factor. Movement latency (ML) had a significant main effect for condition (*F*(4183,5)=127.15, *p*<.005) but no eccentricity or interaction effects.

As reported in the first part of phase three of the analysis, baseline fast and slow reaches (BP.F. and BP.S.) had significantly different movement latencies with fast baseline having the shorter ML (see figure 12). Differences between PR fast and PR slow (PR.H.S. and PR.H.F.) were also significant ($Mdiff$(4183)=.09, SEM=.01, $p<.005$) with fast reach once again having the longer MLs. WR slow and fast reaches (WR.H.S. and WR.H.F.) were also significantly different for ML ($Mdiff$(4183)=.04, SEM=.01, $p<.005$) and once again fast reaches were paired with faster MLs.

Slow movements were associated with slow MLs as mentioned in phase two of the analysis. As with the previous low-load movement time analysis, reach time was not considered other than to check the data conforms to expectations regarding the movement duration of the point.

a) Movement Latency   b) Reach Time

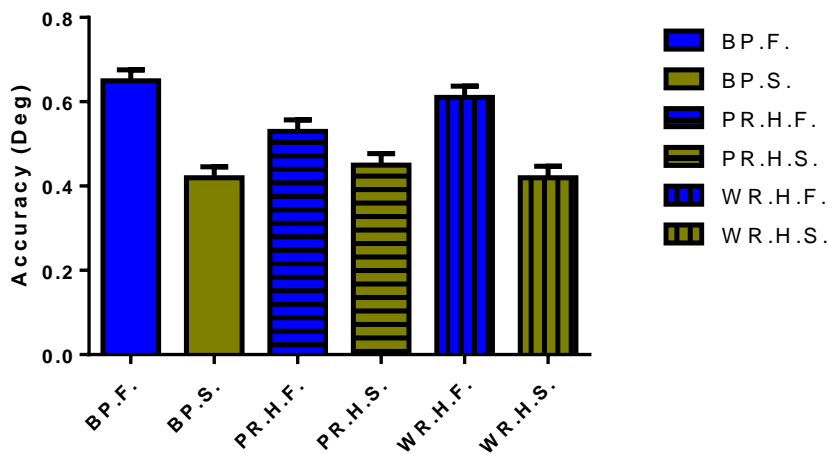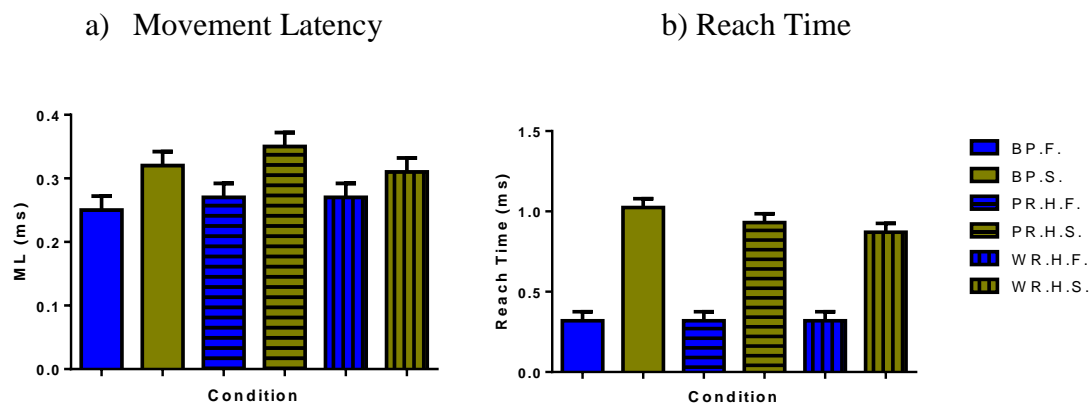**Figure 12** Movement latency and reach time conditions paired with a high-load search task. Data are the mean across all participants and error bars represent 1 SEM. Trials were either under baseline pointing (BP), part reach (PR) or whole reach (WR) conditions, the searches were high-load (H), and accompanied by either a fast (F) or slow (S) reaching movement.

9.5. Discussion

9.5.1. During a single-task search low-load outperformed high-load validating the load manipulation. Findings show a deferential deployment of attention to central vision

Part one of the analysis directly assessed the impact of experimental manipulations, load, condition and eccentricity, on the completion of the central search task. Importantly the high/low manipulation was found to impact the load (or difficulty) of the search task with high-load searches never having a higher rate of correct responses than low-load searches. However, it is apparent that other factors, such as search task length, also impact task performance and this is evident in the significant differences between load conditions dependent upon letter string length. When the letter string was short and resource capacity was not taxed, no difference between high and low-load search performance was found although it was evident in longer searches. These findings are consistent regardless of whether the trial was a single or dual-task condition.

The finding of capacity dependant load impact supports one of the basic assumptions of PLT (Lavie, 1995), however, no condition with a single letter was performed so further comparisons based on search task performance were not appropriate. The differences between high and low-load searches were consistent with those suggested by dilution theory (Benoni & Tsal, 2010; 2013) and were successful manipulators of load once resource demand exceeded capacity.

Somewhat surprisingly, there were few significant differences between search performance under single task and dual-task conditions. This is consistent with an attentional bias towards central vision indicating an attentional distribution construct that supports preferential attentional allocation to central vision (Wolfe et.al 1998; Mackeben, 1990; Beck & Lavie, 2005; Handy, Soltani & Mangun, 2001). Under these conditions, searches displayed

at central vision receive preferential attentional resource allocation. This suggests most of the detrimental impact (if any) would be found in peripheral task performance. The lack of difference found between high and low searches for short letter strings may be representative of a 'floor' effect, a lack of difference based on the ease of the task failing to exceed capacity limits of represented resources. The percentage of correct search responses in strings of the same length differed between single and dual-task conditions for only a single comparison. The division of attention in dual-task conditions negatively impacted performance of the longest search task string. Under these conditions, task load is so high that the central attentional bias is insufficient to compensate for performance degradation.

The first hypothesis which predicted better baseline search performance in low-load conditions attributable to the reduced cognitive complexity of the task was supported. However, this was true only of searches of lengths longer than six letters reflecting the level of resources needed before load effects become evident. The secondary assertion that single-task performance would exceed dual-task performance was not supported by the search task results. This finding was attributed to bias attentional allocation to tasks displayed at central vision under dual-task conditions. The search tasks were found to be adequate tools for load investigations with performances indicating under what circumstances optimal performance can be expected (reflected by the 'floor' effect) and when capacity limits are exceeded (the 'ceiling' effect).

9.5.2. Search task load makes little impact on the planning and execution of goal-directed movements while task switching and target eccentricity have a significant impact on performance

Part two of the analysis focussed on how goal-directed movements are impacted by when in the trial sequence the central task concludes and the associated load of the search task. In order to reduce the complexity of the analysis, fast and slow movements were analysed separately. Therefore although differing patterns of results found for fast and slow reaches are discussed in this phase in a general sense, fast and slow goal-directed movements are not directly (statistically) compared here. The basic premise for this phase of the analysis is the sharing of attentional resources between motor and cognitive systems (Deubel & Schneider, 1996), and the coupling of goal-directed movements with attention (Baldauf et.al 2006). This combined with spatial attentional distributions having been shown to vary in response to task load or complexity (Elliott & Giesbrecht, 2010) leads to an expectation that load may impact the motor system via attention. This attentional modulation allows investigation into task demands and the distribution of attention at different eccentricities impacting upon pointing movements depending on task load conditions.

Regardless of the movement speed, endpoint accuracy was impacted by dual-task, divided attention conditions when compared to baseline performance. However, the effect was confined to the presence/absence of central load and not the search task load manipulation. As dual-task manipulations impact the results it can be inferred that task-load contributes to accuracy performance, unfortunately results were less consistent than achieved via the movement speed manipulation. In 1954 Fitts discussed testing the capacity limits of the speed/accuracy tradeoff by using different tasks. By the manipulation of load, limits to capacity were investigated and found to impact pointing accuracy in addition to the effects of movement speed. As differences between single and dual-task conditions was not universal

(there was no significant difference between BP.S. and WR.L.S.) it suggests decreases in visual information (Yu et.al. 2015) and performance decrements (Plainis et.al 2001) associated with increasing cognitive complexity (load) are not an inflexible rule. Despite this isolated case, accuracy of the movement was generally impacted by the presence of the central task which conforms to past findings that high-load (as opposed to low-load) at central vision degrades peripheral performance (Chan & Courtney, 1993; Carmel, Saker, Rees & Lavie, 2007). There were some differences in the patterns of response accuracy depending on the speed of the movement. When moving slowly, costs associated with switching attention were evident. Conditions in which the search task ceased simultaneously with pointing target presentation (and localisation) were less accurate than both baseline and conditions where the search task continued throughout the reach. The reason this cost was apparent in slow but not fast reaches may be due to the increased accuracy under slow pointing conditions allowing for small but consistent deviations to be observed. Movement endpoints were less accurate when reaching fast reflecting a greater amount of error which may have masked the switch costs were any present.

Movements produced under fast pointing conditions did not display accuracy effects due to load but unlike slow reaches they did reflect a steady difference due to single/dual-task conditions. This is an indication of some degree of interference due to competition for shared resources. Interestingly, the direction of the effect was a consistent improvement in accuracy under dual-task conditions. This facilitation under dual-task conditions is consistent with previous work suggesting primary task performance is boosted when undertaken with a secondary task compared to when performed alone (Balslev et al. 2007; Liu, Miall & Cole, 2008; Enns & Liu 2009; Spataro, Mulligan & Rossi-Arnaud, 2013). Dual-task facilitation can be explained in terms of attentional allocation already being deployed to the visual scene before pointing stimulus presentation, allowing for attentional spreading rather than the

initiation of attentional deployment. This may be particularly relevant when reaching fast as the system is under strain by the movement speed maximising any available benefits. Reaching slowly facilitates the gathering of feedback information and online updating (Saunders & Knill, 2003) and allows ample time to deploy attention. This results in high levels of pointing accuracy regardless of if the trial was conducted under single or dual-task conditions.

Changes in pointing accuracy as a result of target eccentricity were evident with decreased accuracy being associated with increased eccentricity. This is consistent with past research which has attributed this effect to reduced acuity making localisation information coarser grained (Anstis, 1996; 1998). Greater attentional deployment has also been found for targets closer to central vision compared to those at greater eccentricities (Petrov & Meleskevich, 2011; Long & Ma-Wyatt, 2014). Movement endpoint precision was not impacted by load or experimental condition in either slow or fast reaching conditions. Although no directly comparable findings appear in the literature, eye movements have been found to have load dependant changes to precision (MacInnes & Hunt, 2014). This suggests ocular and motor movement systems may respond differently to manipulations of load although this would need validation by future research.

Theoretically according to PLT, pointing paired with low-load searches should be performed better (more accurately) based on the premise that attention processes all within its capacity. With low-load conditions there should be more resources in reserve to process the pointing target, compared to high-load searches which would have less resources to allocate to the peripheral task. The failure of search task load differences to impact pointing accuracy may be attributable to the experimental design. In PLT the stimuli not relevant to the search task are distractors, in our design the secondary stimuli is the pointing target and so is still task relevant. This reflects a fundamental difference in the approach taken in the study of

visual stimuli processing. If attention processes to its full capacity automatically the goal driven nature of the peripheral target should not impact resource allocation which is already deployed to its full extent. Past research has suggested the existence of an 'attentional window' or an area of enhanced processing which can be modified by top-down goals (van Beilen, Renken, Groenewold & Comelissen, 2011). This suggests a difference in the underlying mechanism operating between peripheral stimuli and peripheral distractors. Future research is essential to ascertain the relationship between the goal-driven nature of visual stimuli processing and task load or complexity.

When making a slow goal-directed movement, ML failed to show a consistent pattern of effects attributable to the load of the concurrent search task. Only in one dual-task condition did performance vary significantly from single-task baseline performance; WR paired with a low-load search produced increased ML levels. Generally when making a slow movement the addition of a secondary task did not cause ML to deviate from baseline levels, this was true regardless of the load of the search task.

The reach times of slow goal-directed movements showed strong dual-task effects with every dual-task condition having reach times significantly different to baseline performance. Dual-task conditions universally produced reach times that were shorter than those obtained when reaching without a concurrent central search task. The notion that reduction of reach latencies can be attributed to load conditions finds support in the pattern of results found when taking the associated load of the search task into account. Reach times appear to speed up as task load increases when making a deliberately slow movement. The inclusion of an additional task (dual-task conditions) increases trial complexity thereby increasing task load. Therefore performance fluctuations attributable to the addition of a second task to the trial can be considered the result of changes in task load.

Although both high and low load searches decreased reach time relative to baseline, high-load conditions resulted in faster reach times than low-load. Conditions which had search tasks that continued throughout the reach (WR) did not show performance impacts due to search load. This does not necessarily undermine the argument that search load impacts reach time, as WR conditions had the fastest reach times and that finding supports the idea that task complexity speeds slow reaches.

A different pattern of effects for ML and reach time was found between fast and slow reach conditions, contingent on experimental condition. But as with slow reaches, search task load made no impact on either movement time measures when moving quickly. Due to the restricted time available for feedback during fast reaching, any impact of load on online updating was not expected to be observed. However, load was not found to impact reach time (when updating to the movement occurs) when reaching slowly indicating the cognitive factor of the search task, load, did not impact pointing updating which is also a cognitively based mechanism. MLs were shorter in single-task baseline condition (BP) than either dual-task condition (PR & WR). These results suggest that the time needed for movement planning is negatively impacted by the added complexity of the presence of a second task. The interference evident suggests shared resources exist between search processing and movement planning. Furthermore disengagement of attention to the central task during peripheral pointing target localisation (PR) was found to have a generalised negative effect on ML with latencies longer than in conditions where the search continued through the reach (WR).

Reach times for fast goal-directed movements were unaffected by search task load but were impacted by experimental condition (BP, PR & WR). Reach times were generally performed at baseline levels when the central search task continued throughout the reach (WR). However when the central search was disengaged partway through the reach, the time

taken to complete the fast reach was shortened (PR). It appears that under PR conditions ML is lengthened but reach time is reduced, suggesting a cost to disengagement from the search during localisation resulting in a lengthened ML. However, the accompanying reduction in reach time compared to search continuation suggests there is also a cost to reaching when the search continues throughout the reach. This indicates performance of a cognitive search shares attentional resources with both stages of the movement. The eccentricity of the pointing target did not impact either the ML or RT variables.

The hypothesis of goal-directed movement being performed less accurately under dual-task conditions was only partially supported by the results. ML was longer than baseline in dual-task conditions supporting past findings that pre-movement planning time is negatively impacted by simultaneously engaging in two tasks (Long & Ma-Wyatt, 2014). There were also instances of dual-task facilitation such as the accuracy of fast reaches increasing under dual-task conditions, which may be due to pre-engaged attention proving more beneficial than initiating attentional deployment. Consistent eccentricity effects for accuracy were found, with greater eccentricities associated with less accurate movement endpoints. However, despite past findings suggesting a possible link between cognitive load and goal-directed movement (such as central load reducing peripheral cortical activation (Handy et.al 2001; Schwartz et.al 2005)) there was little evidence in the results of movement performance being impacted by central search task load. Interestingly, task conditions seemed to produce a different pattern of results depending on the speed of the reach but as reach latency conditions were not directly assessed in this phase of analysis we were unable to draw conclusions as to the significance of these differences. This led to a final phase of analysis where an LMM analysis was conducted investigating the impact of pointing speed on movement outcome measures.

9.5.3. Manipulation of movement speed produce consistent and predictable impacts upon outcome measures

In part three of the analysis, experimental condition (BP, PR & WR) effects were as discussed in phase two and load conditions were analysed separately to isolate effects attributable to movement speed alone. Although the literature is sparse, the finding that cognitive load failed to impact movement is not unprecedented. Kannape et.al's (2014) study looking at goal-directed walking found performance of a high-load task did not impact the enactment of the movement. However, they did find interference with the speed of walking suggesting a link between load and movement speed.

There was a highly consistent pattern found for the accuracy of movement endpoints with slow movements being significantly more accurate than fast movements. This holds true for all experimental conditions (BP, PR & WR) regardless of the load of the accompanying search task. This is consistent with there being a trade-off between movement speed and accuracy as conceptualised as Fitts' law (Fitts, 1954).

When the goal-directed movement was performed without time pressures during slow reach conditions, both ML and reach time were significantly slower than when performing fast reaches. Reach time was specifically modulated by instructions to point slowly or rapidly so differences to this outcome measure reflect successful compliance to this experimental manipulation. Interestingly, for all experimental conditions and regardless of search load, ML, reflecting pre-movement planning time, also consistently increased under slow movement conditions.

The impact of movement speed on pointing produced consistent results. Reaching slowly produced greater accuracy than fast movements. However as significant condition effects were also evident, the interaction between speed and accuracy appears to be modulated by task difficulty under dual-task conditions. This supports Fitts (1954)

conceptualisation of the speed/accuracy tradeoff as a way to investigate the information capacity of the motor system. When fast pointing, ML was faster than when producing a slow reach despite receiving the same directions to respond to the target as soon as it was perceived. This is curious as the instructions to participants only specifically mentioned a modulation of reach time. Moving fast places stress on the system and as such increases task difficulty conceptually making specifications about moving speed a manipulation of task load. Furthermore speed modulations had consistency of findings compared to the lack of impact attributable to cognitive load and the unpredictability of the significant results that were found. This suggests that experimental manipulation of load associated with a movement task would be better achieved by the manipulation of the movement speed rather than changes in cognitive complexity.

9.5.4. Overall conclusions

Although baseline searches confirmed the load manipulation to be valid, overall search task complexity had little impact on goal-directed movement under dual-task conditions. Load influences were apparent in single task but not dual-task conditions reflecting fundamental differences to task performances which support this comparison having underlying mechanisms not totally dependent on task load. This suggests these conditions represent more than a low/high-load division which is consistent with suggestions raised by Dilution Theory (Benoni & Tsal, 2010) regarding possible confounding influences to load category construction.

The failure of the search task to be negatively impacted by dual-task conditions is suggestive of preferential attentional deployment to central vision. The accuracy of pointing movements showed consistent degradation with increased eccentricity. Together these

findings support the graded attentional window theory of attention (van Beilen et al, 2001). Attentional resources (and the increased processing capacity associated with them) are heavily deployed at central vision and progressively less resources are available for processing with increasing distance from this point.

As discussed above, manipulation of cognitive load by changing the search task characteristics (which in turn increased overall dual-task task difficulty) was less efficient and consistent as a load manipulation for goal-directed movements than movement speed was. This suggests the speed of the movement undertaken itself can be thought of as increasing the load associated with carrying out the movement and could therefore be pivotal to studies of goal-directed movement and load.

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10. Conclusion

The experimental manipulation of the search task successfully impacted performance with high-load searches being associated with poorer performance than low-load searches, displaying its adequacy as a tool for load investigations. Few significant dual-task effects were found for search task performance supporting the findings in study one and two of preferred attentional deployment at central vision. The load of the central search task had little impact on movement performance. However, dual-task costs were seen with decreased endpoint accuracy associated with increased target eccentricity supporting a similar finding in study two. Consistent patterns of results were found when directly comparing reaching outcomes under fast and slow movement speeds. Slow reaches have more accurate endpoints than fast reaches and faster reach times are paired with faster movement latencies. This study contributes to the overall aims of this thesis with the suggestion that while task load is important in terms of attentional distribution, when studying goal-directed movements manipulation of load should be achieved via variations in movement speed rather than the traditional cognitive load manipulations.

11. Exegesis

11.1. Summary and comparison of the results from the three studies highlighting the original contributions of each study

Study one looked at dual-task enactment of a central search task and a goal-directed peripheral pointing task, made with a fast pointing speed. The dual aims of the study were to validate a new experimental design and to assess if the cognitive and motor tasks shared attentional resources. The novel experimental design was found to provide insights into the outcome measures relevant to our studies aims. Therefor providing evidence that this design provides a useful and valid tool for future studies. Task performance was possible under dual-task conditions and in many cases performance matched single/undivided attention conditions. Unique to this study, the results showed that there were costs associated with the deployment of attention away from the pointing task, however, effects were found for only the planning segment of the task leaving the duration of the hand in flight unaffected. The movement latency was longer under dual-task conditions; this indicated that resources were shared between the cognitive and motor tasks increasing the time taken to construct the initial movement plan.

Study two's aim was to address the limitations involved in study one's focus on fast movement durations and resolves this by use of the same design but performed using slow pointing movements. The aim was to assess if the limitation of updating time with fast movements masked possible attentional sharing between the cognitive task and the hand in flight segment of the pointing movement. The results showed dual-task impacts were evident in the initial planning time (movement latency), supporting the results of study one. Unlike the first study, the time the hand was moving was also impacted by dual-task conditions supporting the hypothesis that updating has an attentional component when reach duration is

long enough to allow a high degree of online updating. This result also provided a novel contribution to the literature as the impact of attention on this reaching phase was an issue unresolved until now. Results also indicated endpoint accuracy was impacted by the eccentricity of the pointing target, a result that was not evident in study one. This suggests the change in movement duration impacted movement endpoints, possibly due to fast reaches producing less accurate endpoints the variability of which masked the small constant error produced by differences in eccentricity. Also in contrast to study one, the central search task was not impacted by dual-task conditions this supports the suggestion in past literature that central vision has a privileged position in regard to the allocation of attention. It is suggestive of slow reaches not taxing the system to a degree which overcomes the attentional bias towards central vision as fast reaching does.

In study three, I sought to quantify the differences in the results between study one and two by making direct statistical comparisons between fast and slow goal-directed movements. It was also designed to round out the investigations into the dual-task paradigm via manipulation of the previously static central search task. The alphanumeric search presented in studies one and two was defined as a high-load search while another search which was the same in terms of how many letters were in the string but limited the letters shown to two (the target 'H' and distractors 'O') was designated as the low-load search. Both types of searches had two possible speed conditions, fast or slow, which accompanied the search in dual-task trials. Results supported the high/low load search manipulation with low-load being performed more accurately than high-load searches. Also supporting the experimental manipulation both a floor and ceiling effect was evident indicating that all levels of performance associated with the task are investigated within the design. These manipulations expanded on the unique experimental design giving it the ability to be used in a greater variety of ways.

While some differences in pointing performance could be attributed to search task load condition, however, these differences were not consistent. Although the manipulation of search task load resulted in inconsistent results, visual elements such as eccentricity and the speed of the pointing movement did give a high degree of consistency in their results. Greater eccentricity was associated with less accurate movement endpoints, as may be expected by decreasing acuity with distance from central vision. A comparative analysis of slow and fast movements results indicate the speed of a pointing movement produces endpoint results that are consistent and provide a predictable pattern of effects. The endpoints of slow goal-directed movements were more accurate and the movement latency, reflecting pre-movement planning time, was longer when compared to fast movements. These results reflect several unique contributions to the study of load, attention and goal-directed movement. While changes to the central search task impacts attentional dispersion, such as variations in bias in central attention and decreased accuracy performance to a briefly appearing target with eccentricity, it was not the most effective manipulator of task load. When completing a reaching movement simultaneously with a cognitive task the most reliable way to manipulate task load was by changing the speed of the movement.

11.2. Possible future directions for research based on the findings from this thesis

When addressing the possible future directions which arise from this thesis two distinct avenues for investigation are clear: future studies that will build on the findings of the studies undertaken, and areas of research based on the suitability of the experimental design to investigate an issue. Two possible areas for future directions in research based on each of these avenues will be discussed. The topics generated as logically following from the findings presented in the thesis are the idea of movement speed as a load manipulation for goal-directed movements and the assessment of attentional dispersion across the visual field.

Based on experimental design suitability for areas of investigation ageing, load and motor movements will be discussed, as will the area of eye movements.

11.2.1. Future directions based on the findings from studies contained in this thesis

Supporting past research (Wolfe, O'Neill & Bennett, 1998; Mackeben, 1999; Beck & Lavie, 2005; Handy, Soltani & Mangun, 2001) several of the current results suggest central vision receives preferential attentional allocation when stimuli appear in that visual region. Our studies showed limited dual-task effects for central search task performance while changes in performance of the peripheral task were found. Although the basic bias is well supported the specific parameters of it require further investigation. The current studies employed a design which only presented targets at two eccentricities (4º and 8º), the closest of which was still 4º away from central vision. If the pointing targets appeared at more eccentricities the result would be a finer grained sample. This would allow investigation into the fluctuations of attentional deployment and the rate of decay of the central vision attentional bias. Past studies suggest attentional impact on goal-directed movement is dependent on the targets distance from central vision (Baldauf & Deubel, 2008; Juola, Bouwhius, Cooper & Warner, 1991; McKela, Rovamo & Whitaker, 1997) yet the details remain unclear. For example, it is unclear if attention gradually diminishes with eccentricity or if the divide between visual regions is more defined. Past studies have had results that seem to support the distribution of attention fluctuates in rings around central vision (Juola et al, 1991), others would better fit the conceptualisation of a gradual decline of attention with eccentricity (Van Beilen, Renken, Groenewold & Comelissen, 2011). This graded attentional design has been described as a graded attentional window (Van Beilen et al, 2011) but fluctuations are possible and results of a detailed investigation may not be a perfect fit for either design. Results from the third paper which found endpoint accuracy decreased with

eccentricity are not able to resolve this issue as samples were only taken at two eccentricities. Although beyond the scope of the current study, increasing spatial sampling would provide valuable information on the allocation of resources in response to task demands. The experimental design suits this aim as it allows for targets to be presented at any location around the central task and at any eccentricity within the monitor's frames. The design also allows for manipulations of task load and investigation into the impact of fluctuating task demands. Task complexity (reflecting load) has been found to mediate spatial attention (Elliott & Giesbrecht, 2010) and low-load tasks at central vision are paired with better performance on a peripheral task than high-load dual-task conditions (Chan & Cortney, 1993; Carmel, Saker, Rees & Lavie, 2007). However the results of the load investigation in paper three suggest that when investigating a cognitive and motor task, fluctuations of movement speed may be a more reliable manipulator of load than more traditional manipulations of cognitive load.

Another interesting avenue of investigation suggested by the current research is the role of movement speed in patterns of attentional deployment to a movement goal and its ability to modulate the load of the task. The interaction between enactment of goal-directed movements and the concurrent performance of a cognitive task is currently gaining interest as an area of investigation, however more investigations are required before we have a full understanding of the topic. Many of the studies to date have focused on walking movements and this is an important area to study as it relates to injury due to a fall prevention and represents a motor movement essential to daily life. A complex task and walking have been found to compete for resources under dual-task conditions (Schaefer, Schellenback, Lindenberger & Woolacott, 2015) which suggests cognitive and motor systems share cross-domain resources under these conditions. The nature of the interaction between cognitive and

motor systems requires further investigation with the understanding task difficulty could also impact dual-task performance.

The dual-task cost on walking has been found to be dependent on cognitive task complexity when engaging in both a cognitive and motor task (Patel, Lamar & Bhatt, 2014). In the results of paper three the manipulation of cognitive load was found to have an inconsistent impact on pointing movements. However, the speed of the movement operated in much the same way as a manipulation of load could be expected to, with increased speed equating to increased load, and provided more consistent effects. Past research supports a link between movement speed and cognitive load, Knappe, Barre, Aminian and Blanke (2014) studied walking movements and cognitive load and found the load manipulation failed to impact movement enactment but it did impact the speed at which it was made. Clearly further investigation into the relationship between task load and movement speeds, along with fine hand movements in general needs to be done. There are several reasons the current experimental design is suitable for use in these investigations, it was designed and used in the current studies to examine the cognitive/motor dual-task interactions under different task demands. It offers single/dual task comparisons of both cognitive and motor tasks each of which are able to be modified to fit the aims of the experimenter if desired. Under these dual-task conditions performance also depends on attentional and visual factors, such as eccentricity. The design of the experiment takes these factors into account and allows information collection on their performance.

11.2.2. Future directions based on the suitability of the experimental design to investigate an issue

In experiments presented in this thesis, pointing under dual-task conditions harnessed covert attention, decoupled from eye movements. However, many tasks may not need

constant fixation differing from the experiments search task. In these instances the eyes may be moved to provide the best performance of both tasks. Natural human vision does not keep the scene static, saccades are made to possibly task relevant or salient locations building up a three dimensional 'map' of the scene. As saccades are integral to normal spatial information acquisition it's important to understand how eye movements operate with hand movements under dual-task conditions. The experimental design allows for alterations, such as the use of an eye tracker rather than a touch sensitive monitor to record endpoints, but the basic dual-task design could be used to investigate interactions between cognitive factors and eye movements. The current studies had a condition where the central search task ceased with pointing target localisation and another which continued throughout the movement. In eye movement studies it would be necessary to use only the condition where the search ends with movement target presentation to allow the eyes to move to the peripheral target. This experimental manipulation was found to have little impact on task performance in our studies so the removal of the other condition could not be expected to impact study results. The load manipulations the design allows could aid experimental aims as load has been found to impact the precision of eye movements (MacInnes & Hunt, 2014). There are indications that this does not reflect the whole story and different aspects of the oculomotor control system may have individual resource pools. Gerardin, Nicolos, Farne and Pelisson (2015) found saccade adaptation (which maintains accuracy of saccades) shares neural substrates with attentional load. Another area where the study of eye movement under cognitive load could be applied is motor movements and ageing. Older adults have been found to have different fixation strategies when cognitive demand is increased and have higher error rates and slower eye and hand movements (Burke, Poyser & Schiessl, 2015).

Another area that may be able to benefit from the current experimental design is study into ageing and motor movement. Decrements in aspects of motor task performance is often

associated with ageing and often studied in terms of cognitive and motor system interactions. In a study of motor control and ageing, brain activation has been found to differ between young and older adults (Seidler, Bernard, Burutolu, Fling, Gordon, Gwin, Kwak & Lipps, 2010). Older adults have a wider spread of activation to motor control areas of the brain, specifically the prefrontal cortex and the basal ganglia, than young adults do. This area of study is important as these areas are susceptible to age-related effects and an understanding of the mechanisms at work may lead to therapeutic or preventative countermeasures. Studies of aging and motor movements often include cognitive load as a factor of interest when observing these interactions. It appears how load impacts the system may be age specific, walking has been found to be differentially effected by a difficult cognitive task with young adults exhibiting increased gait regularity and older adults becoming less regular (Verrel, Loven, Schellenbach, Schaefer & Lindenberger, 2009). There is evidence that the ability to integrate cognitive and motor tasks simultaneously declines with age, with increases in cognitive load resulting in poorer walking performance (Schaefer et al, 2015) and costs to coordination in rhythmic movements (Fujiyama, Hinder, Garry & Summers, 2013).

While much of the literature on goal-directed movements, ageing and load has focused on walking and gait, hand movements are also essential to daily life and deserve attention. The demographic in the current studies were too young for ageing studies but older participants with normal vision could be tested and the experimental design could accommodate load manipulation on either of the dual-tasks being undertaken to assess the resulting impact on pointing movements. The circular array of possible pointing targets would allow testing of different regions in visual space that may be of interest if studying deficits in areas of special vision, such as can be found in glaucoma studies. It is possible this could be useful for a lifetime approach to ageing as young along with older adults are

influenced by cross-domain resource competition when engaged in difficult cognitive/motor dual-task conditions (Schaefer, Jagenow, Verrel & Lindenberger, 2015).

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