An examination of adaptive behaviour when stepping onto moving surfaces: an affordances and agency perspective

PhD Thesis

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The thesis is submitted in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy of the University of Portsmouth.

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ABSTRACT

Fall-related injuries during daily locomotion suggest that ‘every-day’ challenges exceed the capabilities of some pedestrians, with older adults a particular at risk population. Indeed, stepping onto moving surfaces (such as escalators and travellators), represents one every-day locomotor challenge that can lead to accidents. This thesis aimed to examine the perceptual-motor behaviours that underpin successful locomotion as younger and older adults negotiate the challenge of stepping onto moving surfaces, and subsequently explore the use of environmental design as a means of soliciting behaviour change. To achieve this, an integration of optoelectronic motion capture and mobile eye-tracking was used during a series of experiments, which examined: (i) how 12 younger (18-40 years) and 15 older (>60 years) adults stepped onto static and moving surfaces (with and without accuracy demands); (ii) how these participants adapted perceptual-motor behaviours when high contrast demarcation lines and foot targets were added to the moving surface; and (iii) how 11 younger and 14 older adults adapted their perceptual-motor behaviours when a high contrast foot target line was added to the walkway approaching the moving surface.

Results showed that step length increased when stepping onto moving surfaces (younger adults: 62.9cm and 68.6cm; older adults: 59.1cm and 62.0cm; static and moving surfaces, respectively) but reduced when accurate movement was demanded (younger adults: 67.8cm and 63.8cm; older adults: 63.3cm and 59.8cm; no accuracy and accuracy demand, respectively), suggesting environmental design solicited different behaviours. Likewise, design interventions, such as demarcation lines and foot targets added to the simulated escalator environment, invited different behavioural adaptations. Increasing visual salience - adding high contrast lines and/or foot targets to the moving surface - resulted in significantly later gaze transfer from the final walkway footstep location compared to conditions without salient features. A foot target positioned on the approach to the moving surface reduced walkway viewing by 11.32% and increased moving surface viewing by 11.62%, indicating feed-forward control.

Younger and older adults' behaviours consistently differed. Older adult approach times (between 0.15s and 0.19s) were more variable than younger adults (between 0.08s – 0.11s) when overcoming environmental challenges, indicating that older adults adapted their approach to a greater extent. Moreover, interventions invited different behaviours between age groups. The approach target line invited later gaze transfer in younger adults preceding final walkway foot contact, but earlier gaze transfer in older adults (younger adults transferred gaze 332ms and 237ms; older adults transferred gaze 247ms and 447ms; no target and target conditions, respectively). Such differences suggest that, unlike younger adults, older adults did not adopt online control, which may be due to the limits of their action capabilities.

Overall, this thesis demonstrates that differences in adaptive perceptual-motor behaviours between younger and older adults arose from functional differences in their action capabilities and properties of the moving surface environment. Subsequently, the thesis also provides evidence to help inform safety policy and improve escalator user safety.

DECLARATION

Whilst registered as a candidate for the above degree, I have not been registered for any other research award. The results and conclusions embodied in this thesis are the work of the named candidate and have not been submitted for any other academic award.

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Finally, I dedicate this thesis to Mum, Dad, Ben, and Becca, and would like to thank them for their limitless support.

DISSEMINATION

Publications

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Invited presentations

Hunt, R. 'Escalators and Ageing', Invited presentation, University of Portsmouth Ageing Network (UPAN). Portsmouth, UK 05/2018.

Hunt, R. 'An overview of adaptive locomotion', Invited presentation, HSE Steering group meeting - Preventing Escalator falls, London, UK., 06/2018.

Hunt, R. 'The Biomechanics and Motor Control of Human Gait when Transitioning onto Moving Surfaces', Invited presentation, HSE Steering group meeting - Preventing Escalator falls. Portsmouth, UK., 06/2019.

Hunt, R. 'Escalator Safety Interventions: a Naturalistic Enquiry', Invited presentation, Heathrow airport management. London, UK. 11/2019.

Hunt, R. 'Inviting safer behaviours when Transitioning onto Moving Surfaces', Invited presentation, HSE Steering group meeting - Preventing Escalator falls. London, UK., 06/2020.

Hunt, R. 'The Control of Human Gait when Transitioning onto Moving Surfaces: Next Steps', HSE Steering group meeting - Preventing Escalator falls. London, UK., 10/2020.

Hunt, R. 'The control of movement during complex locomotor tasks' Invited presentation, University of Portsmouth PGR seminar series. Portsmouth, UK 10/2020.

CHAPTER 1: GENERAL INTRODUCTION

As an adventure sports coach I often observe individuals struggling to overcome environmental challenges. In an adventure sports context, these challenges may be an overhanging cliff to climb up, a set of demanding rapids to kayak down, or a narrow mountain ridge to traverse. Successful performance in these environments is predominantly characterised by an individual's ability to independently overcome challenges without mistake or incident, and achieved using a niche set of skills honed over years of training (Collins & Collins, 2013; Immonen et al., 2018). Empirically, the study of skilful human perception and action under conditions of environmental challenge have commonly been examined in competitive sport situations, such as between-athlete interactions (e.g., avoiding a rugby tackle), high anxiety settings (e.g., saving a penalty kick), or intercepting moving targets (e.g., catching a fly ball). Thus, whilst it is acknowledged that sport comprises instances of people performing at the limits of their perceptual-motor capacity, everyday urban or public environments tend to not be considered in the same vein. However, urban environments are utilised by a much greater volume of people, and although many everyday behaviours may not present the same challenges as high-level sport, there are equivalent demands, including anxiety inducing environments (Ellmers & Young, 2019), avoiding collisions with other people (Dicks et al., 2016), or avoiding moving obstacles (Cinelli, Patla, & Allard, 2009). Successfully negotiating these everyday urban settings often place frail or older adults relatively closer to the limits of their capabilities (Clark, 2015; Hausdorff et al., 2005; van Andel et al., 2018b). Moreover, in extreme cases, failing to overcome these everyday challenges has been associated with falling, which for frail, older, adults carries severe consequence and has been identified as one of the leading contributors to loss of life (Foster et al., 2014; Rhea & Rietdyk, 2007; Rubenstein, 2006a).

1.1 Overcoming environmental challenges

The consequence of falling has spurred research exploring human adaptive behaviours when negotiating commonly encountered locomotor challenges (Foster et al., 2014; Hsu et al., 2015; Zietz & Hollands, 2009). Extant research has established that regardless of a person's capabilities, the ability to remain stable while walking may be complicated by many environmental factors. Classifying successful locomotion as a person's ability to overcome environmental challenges without a physically harmful, or energetically costly loss of balance (Donelan, 2016; Kuo, 2007), researchers have evaluated human adaptive behaviour as participants negotiate a myriad of challenges commonly encountered throughout daily life, including: avoiding an obstacle on the floor (Marigold, 2008); negotiating an approaching pedestrian (Dicks et al., 2016); avoiding contact with a closing aperture (Cinelli & Patla, 2008); adapting to surface properties, such as changes in friction (Cham & Redfern, 2002) or compliance (Dickinson et al., 2015); or stepping onto moving surfaces, such as escalators or travellators (Hsu et al., 2015). Examining the behaviours people utilise to successfully overcome such challenges has established that the ability to adapt perceptual-motor behaviours is a skill utilised by people of all abilities that – unlike sport – emerges without specialist training (Barton et al., 2017).

Classified as movements that deviate from steady state patterns, perturbations occur when people adapt their movements to overcome environmental demand (Bruijn, Meijer, Beek, & Van Dieen, 2013). Perturbations are extremely common and experienced by nearly every person on a daily basis (Yoo et al., 2019). For example, perturbations may occur when an individual negotiates uneven pavements, curbs, or obstacles (McAndrew et al., 2011), which may require them to adapt their behaviours in order to maintain balance (Wu et al., 2017), change direction (Bastin et al., 2010), or adapt movement speed (Fajen & Matthis, 2011). Behavioural adaptions when overcoming locomotor challenges have commonly been associated with reducing the extent an individual is perturbed by their environment (Higuchi, 2013). Researchers highlight that adapting movements prior to perturbation occurring, presents the most powerful means of maintaining successful locomotion, and is typically referred to as anticipatory behaviours (Higuchi, 2013).

Individuals may draw on a range of anticipatory behaviours to overcome environmental demands. Typically arising from research that demands accurate movement (commonly referred to as locomotor pointing), such as stepping onto foot targets or avoiding obstacles, researchers have shown that successful locomotion can be obtained through online or feed-forward control modes (Barton et al., 2017; Barton et al., 2019). *Online* control reflects the adaptation of concurrent movement using visual information, such as actively guiding the foot onto a target mid-stride (Matthis et al., 2017) whereas *feed-forward* control pertains to manipulating centre of mass (COM) trajectory over several steps in order to adjust foot position (Barton et al., 2019). Recent proposals (Matthis et al., 2017) have suggested that the two modes of control work in synergy, balancing the compromise between accuracy (via online control) and efficiency (via feed-forward control). From this point of view adaptive behaviours comprising online and feed-forward control have been shown to be robust to both perturbation and changing environmental demand, and can be understood as emerging from the interaction between the individual and the environment (Barton et al., 2017; Harrison, Turvey, & Frank, 2016; Warren, 2007). Consistent with this account, research has highlighted differing perceptual-motor adaptations between different ability groups overcoming the same locomotor challenge (Barton et al., 2019; van Andel et al., 2018b), and within the same group of young adults completing different simple or complex locomotor challenges (Matthis et al., 2018).

Framed within an ecological psychology perspective (Gibson, 1979), Fajen’s (2005) affordance based control offers a theoretical account that suggests people behave in ways that keep the demands of the environment within a threshold dictated by their capabilities (termed action boundaries; Fajen, 2007). Importantly, this account suggests that people regulate their behaviours to remain within a 'safe region', in which they are performing both within their capabilities and at a sufficient rate to overcome environmental demand. As such, evaluating adaptive perceptual-motor behaviours provides a naturalistic window into how the relationship between an individual's ability and the demands of the environment shape adaptive behaviours.

1.2 Inviting safer behaviours

Affordance based control (Fajen, 2005a) offers a reconciliation between two separate avenues of research that have developed under the umbrella of ecological psychology: (i) research exploring the visual control of action, and (ii) the perception of affordances (Harrison et al., 2016), which throughout this thesis, are defined as the invitations for action (Withagen, de Poel, Araújo, & Pepping, 2012). Thus, affordance based control offers examination of how peoples action capabilities influence how they respond to invitations for action. Progressing this theme, environmental design may offer the means to invite 'safer' behaviours in public spaces (Thomas et al., 2021; Zietz et al., 2011). For instance, manipulating an environment's visual characteristics, such as the use of high contrast step edge highlighters, has been shown to positively influence behaviours during staircase walking (Jacobs, 2016). Echoing affordance based control (Fajen, 2005), interventions have been shown to invite distinct behaviours across individuals with different action capabilities (Thomas et al., 2021; Zietz et al., 2011; Zietz & Hollands, 2009). For example, Thomas and colleagues (2021) found that when descending a staircase, the addition of high contrast demarcation lines increased decent speed in older adults whereas younger adults speed was unchanged. These findings imply that the realisation of affordances is a function of the relationship between the properties of the physical environment (e.g., presence of high contrast markings) and an individual’s action capabilities (Withagen et al., 2012).

Although researchers have explored the behaviours of individuals with distinct action capabilities as they over-come environmental challenges in combination with behavioural interventions (e.g., Zietz, Johannsen, & Hollands, 2011), such works have yet to explore the mutuality between action capabilities, environmental challenge, and behavioural interventions through the lens of affordance-based control. As such, this presents an interesting avenue for future research into perception and action as it may promote understanding of behaviours that arise from the individual-environment interaction.

1.3 Aims of this Thesis

The overall aim of this thesis is to examine the perceptual-motor behaviours that underpin successful locomotion as younger and older adults negotiate the challenge of stepping onto moving surfaces, and subsequently explore the use of environmental design as a means of soliciting behaviour change. More specifically, this thesis: (i) develops a method of integrating mobile eye tracking and optoelectronic motion capture to capture participants perceptual-motor behaviours (Chapter 4); (ii) examines the perceptual-motor behaviours of older and younger adults as they negotiate incrementally more complex environmental challenges, including static and moving surfaces, with and without accuracy demands (Chapter 5); (iii) evaluates the interventions of high contrast demarcation lines and foot targets, which are currently applied to escalator surfaces to improve passenger safety (Chapter 6); (iv) explores whether interventions that invite feed-forward control may invite safer behaviours in older adults (Chapter 7).

1.4 Structure of this Thesis

This thesis comprises of eight chapters containing four empirical studies. Following this introduction, Chapter 2 aims to provide a review of literature pertaining to human locomotion and presents the conceptual framework within which this thesis is built.

Directly following the review of literature, a Selection of Methods chapter is presented (Chapter 3). Because negotiating moving surfaces represents a novel paradigm, Chapter 3 draws on research evaluating escalator incidents as well as adaptive locomotion literature to justify the demographics of the participants recruited and the perceptual-motor variables measured during the experimental chapters of this thesis. Chapter 3 progresses to clarify the procedures used to calculate each variable as well as a justification of whether adaptations in participant behaviours can be considered beneficial or maladaptive.

Following the selection of methods chapter, Chapter 4 aimed to evaluate the quality of data collected through a novel integration of mobile eye tracking and optoelectronic motion capture. Specifically, the study was designed to explore the accuracy of gaze data throughout linear walking tasks, where participants have been noted as primarily attending to floor based locations (Marigold & Patla, 2008a). Throughout the study the accuracy and precision of point of gaze, expressed within a world centred reference frame, was evaluated as participants attended to floor based targets positioned linearly at a range of 1 – 6m. The findings from this chapter informed the experimental design and data analysis of following experimental chapters.

In Chapter 5 the perceptual-motor behaviours of younger and older adults will be compared under experimental condition that present incrementally increasing difficulty. the experimental design allows comparison between environments that challenge successful locomotion with and without demanding accurate movement. Specifically, I sample environments ranging from non-moving surfaces with no accuracy requirement, through to moving surfaces with an accuracy requirement. The chapters general aim is to explore the mutuality between action capabilities and environmental demand. In particular, the chapter considers if the reduction in action capabilities associated with advanced age are mitigated through adopting predominantly feed-forward control behaviours.

In Chapter 6 I expand on contemporary psychological literature advocating affordances as invitations for actions as well as phenomenological examples from architectural and safety-science based experiments which suggest that environments can invite specific behaviours. I target the lack of research establishing the effect of visual based safety interventions in moving surface environments. In particular, I evaluate two commonly applied visual interventions (high contrast demarcation lines and foot targets) with the aim to explore how older and younger adults are drawn towards invitations for specific actions.

In Chapter 7 I build on previous findings and extant research specifying the importance of penultimate step position in regulating COM trajectory to control movements (Barton et al., 2017; Matthis et al., 2017) to consider if visual based safety interventions positioned on the approach to a moving surface could invite feed-forward behaviours. Because feed-forward behaviours had been recognised as prevalent among older adult populations I examined whether such interventions may invite beneficial behaviours that invited successful locomotion whilst respecting the bandwidth of older adults ‘safe-region’ as dictated by reduced action capabilities.

In the Epilogue (Chapter 8) I briefly elaborate on the implications of the present thesis for theory and research in adaptive locomotion literature.

1.5 Considerations in the present Thesis

The studies in this thesis will be submitted for journal publication. As such, the following format was adopted for all chapters: (i) American Psychological Association (7th Edition) format with English UK spelling, and (ii) Table and Figure numbering re-starting with each new chapter and embedded within the chapter’s narrative.

CHAPTER 2: REVIEW OF LITERATURE

2.1 The control of human locomotion

The study of human bipedal locomotion has been a subject of much investigation, with contributions from an array of different scientific disciplines. By way of example, the predisposition of humans to move in energetically optimal has been considered from an evolutionary perspective, and now reflects a central theme of contemporary human movement science (Selinger et al., 2015). Although many studies evidence that people are remarkably sensitive to the energic demands of their movements (Farley & McMahon, 1992; Finley et al., 2013), it is not immediately clear how this sensitivity influences human behaviours when overcoming the locomotor challenges encountered on a daily basis. Recently, researchers have aimed to address this issue by evaluating peoples behaviours whilst they overcome changing environmental constraints, including flat and rough terrains (Matthis, Yates, & Hayhoe, 2018; Matthis & Fajen, 2014). Adaptations to gaze and locomotor behaviours evidence that when overcoming challenges, participants adapted their gaze behaviours to increase environmental certainty, allowing them to commit their COM trajectory towards future step locations and optimise stable movement at a reduced physical demand. Although locomotor challenges are experienced by all pedestrians, the behaviours people adopt to maintain successful locomotion have been shown to vary.

In a seminal study, Chapman and Hollands (2007) compared the adaptive behaviours of younger, older low fall risk, and older high fall risk adults as they completed a series of foot targeting and obstacle avoidance conditions. Different gaze and kinematic behaviour adaptations were noted between participant groups with older adults transferring gaze away from proximal stepping locations earlier and reducing walking velocity. The authors suggest that age-related decline in action capability may result in such behaviours being utilised by older adults to overcome environmental demands. If so, rather than failing to overcome environmental demands, older adults adopted behaviours that were calibrated to their reduced capabilities. The different behaviours identified between the age groups may have implications for how design based interventions may solicit safer behaviours. For example, interventions that invite behaviours that surpass the action capabilities of the at risk population (e.g., older adults) may not be effective at preventing incidents occurring. However, this is an area that has only recently begun to receive attention (Thomas et al., 2021).

This chapter aims to bring together research investigating how people overcome challenges within their environment. It will start off by considering how people navigate flat, obstacle free terrains and progress to consider locomotion through rough terrain, visually guided locomotion, how an individual’s action capabilities influence adaptive behaviours. Finally, this chapter will bring all these points together to consider how design based interventions may invite safer locomotor behaviours, thus improving performance when overcoming a locomotor challenge.

2.1.1 Locomotion through flat, obstacle free terrain

The ability to navigate safely through the environment is an essential part of daily life. Whilst the class of actions underpinning navigation may take distinctive perceptual-motor styles, such as crawling, walking, running, or jumping, collectively, literature has broadly referred to such actions under the umbrella term of ‘locomotion’ (Higuchi, 2013; Vidal & Lacquaniti, 2021). Despite locomotion being a common occurrence of everyday life, moving in a goal-directed way often poses complex problems. Even when travelling though flat obstacle free environments, human locomotion has been recognised as inherently unstable, predominantly because our bipedal structure means the body’s centre of mass (COM) is outside of its relatively small base of support (BOS) for the majority of the gait cycle (Chambers & Sutherland, 2002; Reimann et al., 2018). Despite instability, human locomotion is extremely efficient. In fact, human predisposition to move in energetically optimal ways is well established and recognised as a central principle of movement science (Hayhoe & Matthis, 2018; Selinger, O'Connor, Wong, & Donelan, 2015).

When humans walk across flat, obstacle free terrain, the control of movement has been proposed to arise predominantly from the body's physical dynamics (Matthis & Fajen, 2014). Specifically, it has been suggested that the steady state gait cycle represents an inverted pendulum, in which the COM vaults over an extended leg during the stance phase, efficiently exchanging potential and kinetic energy with every step (Cavagna & Margaria, 1966). The inverted pendulum model of human ambulation (Figure 2.1) has been widely accepted throughout literature pertaining to both flat, obstacle free terrain (Kuo, 2007) and literature examining the perceptual-motor control of adaptive locomotion as pedestrians overcome the challenges of rough terrain (Matthis, Barton, & Fajen, 2017; Matthis, Barton, & Fajen, 2015).

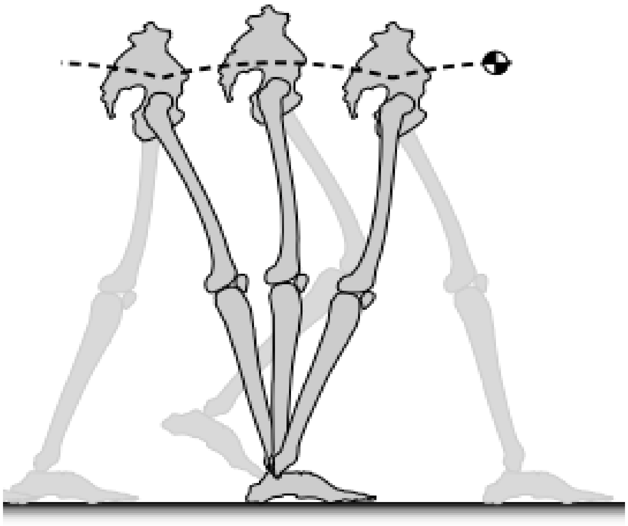

Figure 2.1: The inverted pendulum model Adapted from Kuo (2007)

2.1.2 Locomotion through rough terrain.

The inverted pendulum model (Kuo, 2007) neatly captures human behaviour when walking over flat obstacle free terrain, however, navigating the ‘real-world’ is rarely obstacle free. For example, people overcome challenges that threaten stable and efficient locomotion on a daily basis, including: negotiating closing apertures (Cinelli & Patla, 2008); avoiding other pedestrians (Dicks et al., 2016), and stepping onto moving surfaces, such as travellators and escalators (Beards et al., 2022; Hsu, Wang, Lu, & Lu, 2015). Such challenges are often referred to as the *‘rough terrain problem’* (Warren, 2007) which pertains to how people regulate their behaviours to overcome environmental challenges. In both flat and rough terrain settings, successful locomotion can be defined as the capacity to overcome environmental demands without a harmful, or energetically costly, loss of balance (Donelan, 2016; Donelan, Kram, & Kuo, 2001; Matthis & Fajen, 2014).

Although walking is often considered to be “automatic” and “stereotyped” (Woollacott & Shumway-Cook, 2002), the seminal work of Lee, Lishman and Thompson (1982), which investigated the visual regulation of gait, paved the way for widespread research that has revealed that locomotion is highly sensitive to factors that challenge efficiency and/or stability (Barton, Matthis, & Fajen, 2017; Matthis & Fajen, 2014). During gait, perturbations, which are characterised as deviations from a steady state movement pattern, can be caused by internal (neuromuscular) or external sources, such as avoiding another pedestrian or surface movement (Bruijn, Meijer, Beek, & Van Dieen, 2013; Dicks et al., 2016; Hsu et al., 2015). Aligning with the human predisposition for efficient locomotion, researchers have demonstrated that behavioural adaptations to overcome perturbations are sensitive to the energetic demand of maintaining forward motion (Donelan et al., 2001, 2004; Matsubara et al., 2015). For example, when examining locomotion whilst stepping on sequential foot targets, Barton, Matthis, and Fajen (2019) showed that participants used two different means of controlling movement, classified as either *online control* which entailed 'actively' manipulating foot trajectory mid-stride (e.g., Reynolds & Day, 2005; Weerdesteyn, Nienhuis, Hampsink, & Duysens, 2004), or *feed-forward control*, where participants 'passively'[1] adapted the ballistic movement of their COM over several steps (e.g., Figure 2.2) in order to alter future step position (see also: Barton, Matthis, & Fajen, 2017). These results suggest that people preferred to exploit the pendular mechanics of the body to mitigate the demands of the environment via feed-forward control whilst maintaining efficient forward motion, rather than rely on making more demanding online adaptations to foot trajectory (cf. Higuchi, 2013; Matthis & Fajen, 2014). In both scenarios (online or feed-forward control) visual information is recognised as paramount in guiding movement to successfully overcome environmental demand (Matthis et al., 2017).

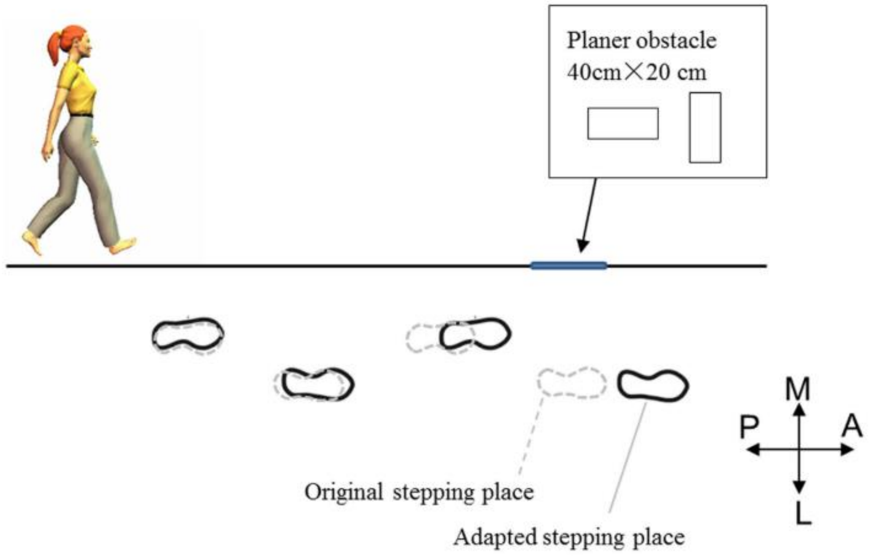

Figure 2.2: Adapting stride length to avoid an obstacle, as an example of feed-forward control. Figure from Higuchi (2013)

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[1] The association of 'active' and 'passive' control as described throughout the works of Barton and colleagues (e.g., 2017) contrasts Gibson (1979) who specifies that visual perception is an active process. Consistent with the wider body of literature associated with ecological psychology, this thesis considers perception and action as an active process.

Although the physical dynamics of bipedal gait plays a key role in locomotion over both flat and rough terrain, evidence indicates that the role of visual information in supporting accurate movement differs considerably between these settings (Higuchi, 2013). For example, when negotiating unconstrained, less challenging environments, minimal emphasis is placed on the visual system to guide locomotion (Matthis & Fajen, 2014), yet when negotiating more challenging rough terrain, people have been shown to balance the demands imposed by the environment's physical structure by adapting gaze behaviours. In an early study to explore the influence of terrain on gaze behaviours, researchers (Patla et al., 1996) established that participants viewed the travel path significantly more when required to step onto foot targets (for comparable findings see: Domínguez-Zamora, Gunn, & Marigold, 2018). Research has also suggested that behaviour adaptations, such as increased exploratory gaze behaviours and reduced walking speeds, increase the time spent viewing the travel path, thereby enhancing pedestrian's certainty about approaching constraints (Matthis et al., 2018). The emergence of behavioural adaptations which promote certainty of distal constraints reflects peoples disposition to maintain efficient forward movement via feed-forward control even when negotiating more challenging terrain (Barton et al., 2019; Ellmers, Cocks, & Young, 2020; Higuchi, 2013; Matthis et al., 2018).

Visual occlusion research has also highlighted the differences between online and feed-forward control in guiding successful locomotion (Matthis et al., 2015). For example, Muroi and Higuchi, (2017) examined locomotor performance as participants traversed a 3m walkway and negotiated an aperture whilst holding a horizontal bar. The participants performed the task under four visual conditions, with vision occluded at different points: (i) after 1.5s static viewing; (ii) after taking two steps and then stopping; (iii) after taking two steps but not stopping; and (iv) not occluded. Findings showed that when online control was prevented by occluding current visual information (e.g., conditions 1-3) fundamental movement patterns, sufficient to achieve some success, were maintained but maladaptive ‘fine-tuning’ behaviours, such as body rotation emerged, which contributed to increased contacts with the aperture. Together experimental works contrasting online and feed-forward control indicate that feed-forward control appears to offer pedestrians a broad level of accuracy at lower physical demand, whereas online control offers pedestrians greater accuracy but at increased physical demand. Consistent with these observations, Matthis, Barton and Fajen (2017) suggested a synergistic relationship between control modes, with feed-forward control affording pedestrians a broad level of accuracy, which in turn enhances the effectiveness and reduces the demand of subsequent online ‘fine-tuning’ movements.

The adaptive perceptual-motor behaviours utilised to overcome rough terrain have been shown to be relational to the demands of the environment. Studies of perceptual-motor behaviour during locomotion have revealed that in non-challenging environments, such as level flat walkways, consistent look ahead distances of approximately two-to-three steps ahead are maintained, suggesting that feed-forward control based behaviours are sufficient to produce safe locomotion through terrain deemed to be unchallenging (Ellmers, Cocks, Doumas, Williams, & Young, 2016; Matthis, Yates, & Hayhoe, 2018). However, when terrain complexity increases, such as when a smooth mountain path becomes rocky and unstable, people have been shown to make more proximal ground-based target-specific visual fixations (Matthis, Yates, & Hayhoe, 2018). Such adaptations have been acknowledged as being at the expense of future planning (i.e., feedforward control) (Ellmers & Young, 2019). Moreover, adapted locomotor behaviours, including reduce stride length and walking speeds have been noted in more challenging environments (see also: Marigold & Patla, 2007, 2008). Corresponding with Matthis, Barton and Fajen (2017), such findings imply that when a broad level of accuracy is required, feed-forward control appears to be sufficient, yet as the environment demands increased accuracy, participants typically deploy an online mode of control. Although research has demonstrated a relationship between environmental demand and adaptive perceptual-motor behaviours (Domínguez-zamora et al., 2020; Marigold & Patla, 2007, 2008; Matthis & Fajen, 2014; Patla & Greig, 2006) the factors that underpin these adaptive behaviours when overcoming locomotor challenges are recognised as being unclear (Domínguez-zamora, Lajoie, Miller, & Marigold, 2020; Domínguez-Zamora & Marigold, 2019; Matthis et al., 2018).

2.2 Visual guidance of locomotion

2.2.1 The control of goal directed locomotion

Successful goal-directed locomotion, particularly when overcoming rough terrain, depends on a person’s ability to gather information pertaining to the environment (Barton et al., 2019). Although literature is largely unanimous that visual information is exploited by the perceptual system, the processes underpinning the control of goal directed movements are frequently debated (Brenner & Smeets, 2015; Katsumata & Russell, 2012; Turvey, 1992; van Soest et al., 2010; Zhao & Warren, 2015). Broadly, two accounts of the visual control of action have emerged: *Predictive* and *Prospective* theories. These accounts differ in the underlying basis for control. For example, predictive accounts suggest action is guided by an internal representation of the physical world (Brenner & Smeets, 2018; Scaleia et al., 2015; Zhao & Warren, 2015) , whereas prospective accounts stipulate that action is guided by current and continuous visual information available during ongoing movement (Panchuk & Vickers, 2009; Zhao & Warren, 2015).

Introduced by Craik (1967), model based control is a predictive account that stipulates that movements are guided on the basis of an internal representation of the body and environment that mediates perception and action. The internal model is based on a combination of external cues (binocular disparity, height in the visual field, and motion parallax) combined with internal information (assumptions and previous knowledge of the environment) and exists prior to, and independent of, action (Hayhoe, Mennie, Sullivan, & Gorgos, 2005). The creation of internal representations of the environment and the body have been commonly alluded to throughout locomotion and space representation research (Etienne & Jeffery, 2004; Glasauer et al., 2007; Scarpina et al., 2017). For example, in an experiment evaluating eye movement during a ball dropping task, Hayhoe, and colleagues (2005) offer support to a model based approach in that participants eye movements accurately pre-empted the balls trajectory. The accuracy of saccades was interpreted as evidence that participants internalised the dynamics of the environment, implementing of a model for action which was not dependent on online visual information. Along similar lines, the ability to navigate to a target following visual occlusion is frequently cited as evidence of an internal representation based system (Loomis et al., 2006). Somewhat paradoxically, reduced movement accuracy and precision when vision is occluded has also been cited as an argument against predictive, model-based, approaches (Zhao & Warren 2017).

In contrast to predictive accounts of visually guided movement, prospective accounts (Fajen, 2007; Warren, 1998) are often applied throughout locomotor and perceptual-motor control research (Barton, Matthis, & Fajen, 2017; van Andel, Cole, & Pepping, 2018). Such accounts suggest information pickup is an active process, with people actively exploring their environment, thus creating changes in the visual field that specify meaningful environmental properties (Withagen & Michaels, 2005). Consequently, movement adaptations modify the performer's relationship with the environment, linking perception and action in a continual cycle. As such, visual information directly guides individual's throughout goal-directed walking without the need for internal models or representations (Fajen, 2007), instead emphasizing the individual's coupling to the environment via optical information (Zhao & Warren, 2015).

Empirical evidence in support of a prospective approach (in locomotion tasks) is recognised as arising from Lee, Lishman, and Thomson's (1982) seminal study, which examined how athletes successfully targeted a long jump take-off board. Focusing on the stride to stride variables of elite long jumpers as they approached the take-off board, Lee and colleagues found that stride length variability was remarkably consistent (less than 3 cm) during the early stages of the approach, yet during the final strides preceding take-off, the participants deviated from a consistent stride pattern, presenting a large increase in stride length variability. Further analysis considering the standard error of step locations showed that the participants did not evenly apportion the adjustment required to accurately target the take-off board throughout the final strides, which would be expected if participants adhered to an internal model. Moreover, as target information was acquired and acted on from a distance using current visual information, this finding was interpreted as evidencing prospective control. Specifically, visual information was utilised to precisely modulate specific gait parameters through a coupling of perception and action. Lee concluded these results indicated a switching in strategy from aiming to produce a stereotyped gait, to actively regulating strides to target the take-off board. However, later research (Montagne et al., 2000) drew from work positioning that the pickup of information could be described as ‘funnel-like’ (Bootsma et al., 1991) to show that the initiation of step length adaptation was proportionate to the amount of adjustment needed. Accordingly, Montagne and colleagues (2000) offered that the entire long-jump approach could be regulated via prospective control suggesting adaptations did not occur throughout the early stages of the approach because the information specifying the required adaptation was too small to be detected by the athlete (for a review see: Barton et al., 2017).

Lee and colleagues (1982) findings have been recognised as a ‘springboard’ for research into the visual regulation of gait (Barton et al., 2017). Accordingly, Lee’s work has been widely replicated and expanded. Consistent findings utilising locomotor pointing tasks have been reported regardless of participant gender or level of expertise (Hay, 1988; Scott et al., 1997) as well as across a range of locomotor settings such as negotiating obstacles (Marigold & Patla, 2008; Moraes, Lewis & Patla, 2004; Patla & Greig, 2006) or rough terrain (Matthis, Yates, & Hayhoe, 2018; Matthis, Barton, & Fajen, 2017). These findings reinforce that the coupling of perception and action is not a skill that emerges only after specialised training or when the environment demands a high degree of precision but represents an essential aspect of human control of locomotion (Barton et al., 2017).

2.2.2 Theories of Prospective motor control

The work of Lee and colleagues (1984), which provided evidence for a coupling between perception and action, was informed by the previously established theoretical work of James Gibson in ecological psychology. Specifically, Gibson (1979) aimed to move away from stimulus-response psychology, instead arguing that the pick-up of information was active rather than passive (Costall & Morris, 2015). Gibson’s ecological approach considered the senses as perceptual systems, which provided a person with the means of seeking out information specifying environmental properties. Pertinent to locomotion, Gibson emphasized the importance of the mutuality between organism and its environment, positioning that through movement, a person creates a spatiotemporal energy pattern - termed optic flow - detectable within the visual array (Bruggeman et al., 2007). Within the optic flow, optical changes (variants) and non-changes (invariants) are proposed to be used in the control of movement. As such, perception enables people to be attuned to environmental properties and control their motion with respect to those properties. For example, features that enlarge through locomotion are detected as getting closer, whereas a change in angle between individual and object denotes a change in direction. As such, changes within optic flow provide information about the effects of movements or the adjustments required for successful locomotion. Consequent adjustments alter the performer’s relationship with the environment, thus establishing that perception and action are linked in a continual and reciprocal cycle. Accordingly, perceptual information is conceived of as information that allows an individual to prospectively control their actions without inferential or constructive operations (Brancazio & Segundo-Ortin, 2020).

Experiments that have manipulated optic flow and examined the resultant changes in action have affirmed that a coupling between perception and action influences the control of movement (Bruggeman et al., 2007; Mohler et al., 2007; Rieser et al., 1995; Salinas et al., 2017). For example, Mohler and colleagues (2007) used a virtual environment to manipulate optic flow as participants walked on a treadmill. Optic flow was altered to be slower than, matched to, or faster than the participants physical gait speed, which was linearly increased between 1.0 and 2.75m/s. Kinematic analysis showed that stepping speed, walking speed, locomotor control, and the speed at which participants transitioned between walking and running, were affected by the change in optic flow. The authors interpreted the results as showing that visual information becomes calibrated to the regulation of gait and therefore contributes to the control of locomotor behaviour. Broadly, theories that centralise the use of information within the optic flow to regulate movement have been termed ‘information-based’ (Fajen, 2007).

According to information-based control, movements are assumed to be guided in a way that produces a desired pattern of optic flow (Warren, 2007). By maintaining the desired pattern in the ambient array, pedestrians effectively ‘null the error’ between their current movements and those required for successful performance (Lenoir et al., 2002). Empirically, experiments exploring how people intercept a moving target, such as a fly ball, often exemplify these error-nulling approaches (cf. Chapman, 1968). When catching a ball, a person moves at a speed that keeps the optical acceleration of the ball equal to zero (Fajen & Warren, 2004). Such an approach often referred to as the bearing angle model (see: Fajen, 2013 for a review), which is based on the premise that if an individual's bearing (i.e., direction relative to some fixed reference direction) and speed remain constant, the individual and the object will intercept (Figure 2.3). Experimentally, researchers have shown participants adapt their approach as a function of their angular velocity to a target, resulting in a constant target-person angle (Lenoir et al., 1999).

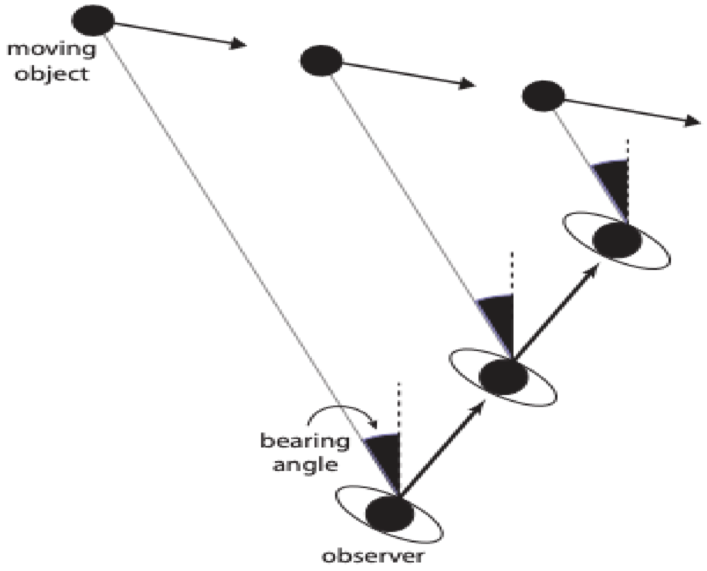

Figure 2.3: The Bearing angle model adapted from Fajen (2013)

Despite popularity in the literature (Michaels & Oudejans, 1992; Zaal & Michaels, 2003), error nulling approaches have been acknowledged as limited in that they do not account for the action capabilities of the actor (Fajen, 2007, 2013; Fajen & Matthis, 2011; Postma et al., 2017). Specifically, error nulling approaches have been questioned due to a failure to adequately consider or explain how individuals abandon the chase when a target becomes unreachable. That is to say, error nulling approaches do not consider that individual differences, such as a fielder's maximum running speed, determine whether a fly ball affords catching

(Fajen, 2013; Oudejans et al., 1996; Postma et al., 2017) or if, when driving, break capacity is sufficient to afford stopping within the required distance to avoid collision (Fajen, 2005a).

The relationship between a person's abilities and environmental demands specifies the opportunities for action that are available to that individual (Withagen et al., 2012). These opportunities are commonly referred to as affordances[2] and epitomise one of the core principles of the ecological approach (Gibson, 1979). Although the information based approach is framed within ecological psychology, it has been suggested that this approach fails to acknowledge an individual's action capabilities (Fajen, 2007). To mediate this limitation, Fajen proposed an alternative account for visually controlled action, *Affordance based control,* which positioned that an actor's behaviour is visually guided by the perception of affordances, which entail the actions available to the actor relative to their abilities.

Affordance-based control has three key contributions that impact the understanding of visually guided action (Harrison et al., 2016). First, affordance-based control emphasizes the actor's sensitivity to their abilities, which underpins their capacity to identify the boundaries separating possible from impossible actions. Secondly, contrasting information-based control, there is no 'preferred state' (such as a constant bearing to be maintained) yet a 'safe-region', in which an actor is performing both within their action capabilities and at a sufficient rate to successfully overcome environments demands. Accordingly, there are countess possible trajectories within the 'safe-region' that correspond with successful performance. Exemplary of this perspective, Fajen (2005) measured deceleration rates when participants were required to break in order to avoid a collision during a simulated motor driving task. Multiple patterns of successful behaviour were demonstrated with participants adhering to the limits of their 'safe-region'. Finally, affordance-based control bridges two major aspects of perception-action

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[2] The concept of affordances shall be explored in greater detail throughout subsequent sections.

research, the concept of affordances and the continuous control of visually guided action which, despite sharing a theoretical grounding in ecological psychology, have been recognised as developing independently (Harrison et al., 2016; Stoffregen, 2000).

The present thesis will investigate the control of locomotion whilst overcoming an environmental challenge from a perception and action viewpoint. As central tenants of ecological psychology, these topics are widely researched yet the definitions of each are frequently inconsistent, a feature noted as common in literature disseminating the works of Gibson (Costall & Morris, 2015). Throughout this thesis, perception refers to the active process of gathering information from the environment and action refers to the use of information for the control of goal-directed movements. The mutuality between environmental demand and human adaptive behaviour has been well demonstrated (Matthis et al., 2018), however, how an individual's action capabilities influence adaptive behaviours has received less attention. As such, in the next section, this literature review will consider research examining how actors regulate movement in accordance with their action capabilities and utilise the affordances offered by cluttered or challenging environments.

2.3 Action capabilities and negotiating rough terrain

Due to the health related consequences of falling among older adults, understanding how ageing has influenced adaptive locomotion has received widespread attention (Scuffham & Chaplin, 2003; Uiga et al., 2015). Accordingly, the behaviours of younger and older adults have been frequently compared, with a relationship between advancing age and cognitive and/or physical decline being well documented (Chapman & Hollands, 2006; Kovacs, 2005; Maidan et al., 2018; Marigold & Patla, 2008; McCrum et al., 2017; Muir et al., 2015; van Andel, Cole, & Pepping, 2018). Despite the great capacity shown by younger and older adults to overcome locomotor challenges, research has highlighted different (mal)adaptive behaviours (Domínguez-zamora et al., 2020; Muir et al., 2015; van Andel, Cole, & Pepping, 2018) and reduced levels of successful locomotion (Schminke et al., 2013) in older compared to younger adults.

Research investigating younger and older adult behaviours when recovering from an unexpected trip indicates that both environmental demand and individuals action capabilities influence adaptive behaviours (Roos et al., 2010). These authors reported that when a trip occurred within the early part of gait's swing phase, an elevating behaviour, where participants lifted their leading limb, was typically used. Alternatively, when a perturbation was caused later in the swing phase, a lowering behaviour where participants altered foot placement to land in greater proximity to their COM, was adopted (see also: Schillings, van Wezel, Mulder, & Duysens, 2000). Building on the inverted pendulum model, Roos and colleagues (2010) noted that an elevating behaviour would be physically more demanding than a lowering behaviour at later stages of the swing phase. Accordingly, the emergence of lowering behaviours later during the gait cycle supports the suggestion that people are sensitive to the demands of adaptive locomotion (de Boer, Wisse, & Van Der Helm, 2010; Matthis, et al., 2019; Roos, McGuigan, & Trewartha, 2010) and that environmental challenges (e.g., perturbation) demand specific adaptive behaviours.

The findings of Roos and colleagues (2010) also highlighted different adaptive behaviours between age groups. Specifically, although both age groups utilised elevating and lowering behaviours, the point in the gait cycle at which elevating or lowering behaviours were adopted differed, with older adults utilising a lowering behaviour earlier in the swing phase than younger adults, and avoiding elevating behaviours later throughout the swing phase. The change in behaviour was associated with physical decline, indicating that adopting elevating behaviours later in the swing phase surpassed older adult's limb strength, reaction times, and movement speeds (i.e., action capabilities; see also: Kovacs, 2005; Liu, Chan, & Yan, 2014; Maidan et al., 2018; Weerdesteyn et al., 2005). These findings imply that the behaviours exhibited when overcoming environmental locomotor challenges are a function of the relation between an actor's capabilities and environmental factors such as the perturbations encountered (Bruijn et al., 2013). Thus, consistent with Fajen's (2007) affordance-based control, such findings point to locomotor adaptions occurring to ensure the demands of successful locomotion (e.g., overcoming a trip) do not surpass an individual's action capabilities (e.g., as a function of age). Moreover, younger and older adults distinct patterns of behaviour when recovering from an unexpected perturbation echoes Fajen's suggestion that rather than a single 'preferred state' dictated solely by the environment, people adhere to a 'safe-region' specified by the relationship between environment and action capabilities. Specifically, in Roos et al., (2010) study, it appears that both older and younger participants overcame perturbation by adapting behaviours with respect to boundaries specified by their action capabilities, yet at a sufficient level to surpass environmental demands. Although findings from perturbation – response paradigms (Roos et al., 2010) are indicative of a relation between action capabilities and adaptive behaviour, such paradigms overlook the role of exploiting advanced visual information's to guide movement when overcoming rough terrain by primarily considering behaviours after perturbation has occurred (Higuchi, 2013). As such, perturbation – response paradigms may contribute limited understanding towards explaining how action capabilities influence perceptual-motor control.

From a perception and action viewpoint, a mutuality between environmental demand and adaptive behaviour has been well demonstrated (e.g., Matthis et al., 2017, 2018), yet research directly aiming to elucidate the interaction between action capabilities, environmental demand, and adaptive behaviour is less commonplace. However, due to the consequence of falling in older adults, several studies have contrasted older and younger adult locomotor behaviours during goal-orientated locomotion. These studies have shown age-related differences in adaptive behaviours (Chapman & Hollands, 2007; Domínguez-zamora et al., 2020; Ellmers et al., 2020). In particular, research comparing young and older adult adaptive behaviours report that older adults prioritise future stepping actions and make proactive adaptations to overcome environmental demand. For example, findings show older adults transfer gaze from proximal locations earlier, give greater attention given to distal areas of interest, and position their lead foot closer to obstacles, than younger adults (Chapman & Hollands, 2007; Domínguez-zamora et al., 2020; Ellmers, et al., 2020; Muir et al., 2015; Young & Hollands, 2010). Accordingly, such findings indicate older adults may utilise feed-forward control to a greater extent than younger adults when overcoming environmental challenges. Because feed-forward control is considered less physically and cognitively demanding than online control (Ellmers et al., 2020; Ellmers & Young, 2019; Holtzer et al., 2015; Wagshul et al., 2019), the emergence of feed-forward adaptations may signal older adults sensitivity to their action capabilities. Consistent with the core principles of affordance based control, such sensitivity might enable older adults to maintain successful locomotion without surpassing the boundaries of their ‘safe-region’ dictated by their reduced action capabilities (Fajen 2007).

Although the actions of older and younger adults have been compared, researchers are yet to explore adaptive locomotor behaviours through the lens of affordance based control (Harrison et al., 2016). Moreover, adaptive locomotion research has primarily manipulated environmental demand by limiting foot holds (Matthis et al., 2015), adding obstacles (Chapman & Hollands, 2007), or including a foot-target (De Rugy et al., 2002), all of which specify that successful locomotion is determined by an individual’s capacity to perpetuate accurate movement. However, building an understanding of perceptual-motor control using paradigms that characterise very specific aspects of human behaviour (e.g., accurate movement) may not represent how people overcome the diverse challenges encountered throughout daily activity, such as stepping onto curbs (Lappi & Mole, 2018; van Andel, Cole, & Pepping, 2018). Therefore, current understanding may be expanded by sampling alternative challenges encountered throughout daily locomotion where success may not be stipulated though realising the demand for accurate movement. In particular, comparing the behaviours of younger and older adults as they overcome such locomotor challenges may help expand understanding of the mutuality between individual and environment (see Chapter 5).

2.4 Inviting safer behaviours

When considered relative to an ecological psychology perspective, adaptive behaviours can be described as complex perceptual-motor skills that arise from the interaction between the person and environment (Harrison et al., 2016; Warren, 1998; Withagen & van der Kamp, 2010). Although people show great ability to maintain successful locomotion (van Andel et al., 2018), failing to overcome environmental challenges carries severe consequence, particularly among older adults, for whom falling is recognised as the leading cause of morbidity and mortality (Rubenstein, 2006b). Alongside the direct health risk to the casualty, injuries linked to falling entail significant financial cost and burden the health services (Carter et al., 2001). Often implemented in public spaces, which challenge successful locomotion, design interventions present a common method that have the aim of soliciting behaviours that reduce the risk of incidents occurring (Kaaronen & Rietveld, 2021) . However, limited research has explored the effectiveness of environmental interventions from a perception and action viewpoint or in relation to the capabilities of the pedestrian (Jeschke et al., 2020). Therefore, this review of literature will now consider how individuals’ realise affordances in order to provide further understanding on why particular patterns of behaviour may emerge.

2.4.1 Affordances as invitations for action

Gibson (1979) proposed that opportunities for action, termed affordances, exist because of the mutuality between the environment and individual. Specifically, Gibson defined affordances as opportunities for action, which were provided to the individual by the environment, stating that “the affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. The verb to afford is found in the dictionary, the noun affordance is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment” (1979, p.127).

Although affordances are a keystone of an ecological approach, they are also much debated in the literature (Chemero, 2003; Costall, 2012, 2015; Withagen et al., 2012). Accordingly, conceptualising affordances remains a contemporary issue that has received much attention (e.g., Costall, 2012; Rietveld & Kiverstein, 2014; Withagen et al., 2012; Withagen et al., 2017). Based on the understanding that affordances are relational to the abilities of the observer, researchers have suggested that affordances are not the causes of behaviour but make behaviour possible (Chemero, 2003; Rietveld & Kiverstein, 2014). Resultantly, affordances are widely considered to be directly perceived on the basis of the actions they offer, but as relations, are not considered exclusive properties of either the environment or individual (Chemero, 2003). This stance suggests that affordances are not relative to an individual as an observer, but as an agent[3] (Costall, 2012). Such an account captures how different surfaces, substances or objects in the environment can afford different actions for different people, for example a cliff

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[3] Providing a full review of agency is outside of the scope of the thesis. Broadly Agency encompasses peoples capability to act independently and make free choices (Littlejohn & Foss, 2009). From an ecological perspective, agency can be understood as an individual’s capacity to execute goal-directed or intentional actions (see: Segundo-Ortin, 2020).

may offer climbing for a skilled climber, a hazardous feature to avoid for a hiker, or an opportunity to get airborne for a BASE jumper (Immonen et al., 2018).

Returning to day to day scenarios, diverse abilities mean that people encounter environments that offer a multitude of actions, and as such, people regularly experience a landscape ‘overflowing’ with affordances (Rietveld & Kiverstein, 2014). For example, a single object (e.g., a chair) affords many actions (sit on, stand on, throw), but the majority of affordances are not realised. Thus, why is an individual drawn to one course of action when multiple affordances are available? Such a question has driven research exploring the nature of the relationship between affordances and agency. As a result, authors (Withagen et al., 2012, 2017) have recently proposed a reconceptualization of affordances, which has implications for how agency may be considered. In particular, following Dreyfus and Kelly (2007), Withagen and colleagues (2012) suggested that affordances are not mere possibilities for action but *invite* specific behaviours (Bruineberg & Rietveld, 2014; Rietveld & Kiverstein, 2014; Withagen et al., 2012, 2017). When considered as invitations, the environment is not comprised of neutral possibilities, but rather comprised of affordances that can attract and repel, thus impacting which behaviours are undertaken (Prieske et al., 2015). Consistent with this concept, Dreyfus and Kelly (2007) outlined the fact that individuals often unreflectively respond to affordances, stating that “we sense the world's solicitations and respond to their call all the time. In backing away from the ‘close talker,’ in stepping skilfully over the obstacle, in reaching ‘automatically’ for the proffered handshake, we find ourselves acting in definite ways without ever having decided to do so. In responding to the environment this way we feel ourselves giving in to its demands” (p. 52).

This account suggests that affordances are directly perceived and experienced as invitations for specific actions, but also that behaviour emerges from the individual-environment system. Consistent with this perspective, examples of affordances soliciting unreflective action when overcoming locomotor challenges can be given, for instance, people commonly pull on door handles, despite knowing a door requires pushing (Desmet & Hekkert, 2007, 2009; Thaler & Sunstein, 2009). Influenced by such an account, Withagen and colleagues (2012) offered an explanation of agency that did not centralise the behaviour of the individual (or animal) but rather focused on the individual-environment interaction. As a result, the authors suggested that behaviour emerges from the interplay between the multitude of invitations offered by the environment, and the individual's capacity to regulate the degree they are drawn to, or resist, action. To explain why a course of action may be taken when many invitations are offered, authors have suggested that affordances vary in the assertiveness of their invitations (Rietveld & Kiverstein, 2014; Withagen et al., 2012). Rietveld and Kiverstein (2014) capture this concept with their proposal of a 'field' and 'landscape' of affordances. They proposed that a landscape encompasses all the affordances that are feasible to an individual whereas the 'field' captures how a collection of affordances appeal to an individual in a certain setting at a certain moment in time (see also: Segundo-Ortin, 2020; Withagen et al., 2017). Research examining sports performers provides multiple examples which neatly capture this aspect of affordances, for instance, a fly ball that may have invited catching at the start of game may not invite the same action later in the game due to fatigue (Fajen, Riley, & Turvey, 2009).

The concept of affordances as invitations for action has frequently been supported through examples from architecture, which evidence environmental design interventions alter an individual's behaviour. Prieske and colleagues (2015) explored the play habits of children in relation to playground design, showing that children jumped between gaps that within their action boundaries. As child development denotes varied action capabilities, their work expanded to suggest healthier behaviours may be solicited through increasing variation in children's play spaces. The invitation of healthier behaviours in 'at risk' populations has been explored by redesigning the 'traditional' office workspace. Taking aim at the health considerations associated with a sedentary lifestyle ,Rietveld Architecture Art Affordances (RAAAF) and visual artist Barbara Visser designed the end of sitting (Figure 2.4) to consider if reconceptualising an office workspace could address such health issues (Caljouw et al., 2017, 2019; RAAAF, 2014). Instead of an office featuring tables and chairs, an office environment was created based on anthropometrical data to ensure the environment did not afford working comfortably from a seated posture. In line with the suggestions of Rietveld and Kiverstein (2014), empirical research evaluating working behaviours within the end of sitting office, identified that workers moved around more often as they transitioned to locations that appeared more comfortable to work in at the time (Withagen & Caljouw, 2016). By creating an environment, researchers established that more active (and thereby healthier) behaviours could be solicited in office workers.

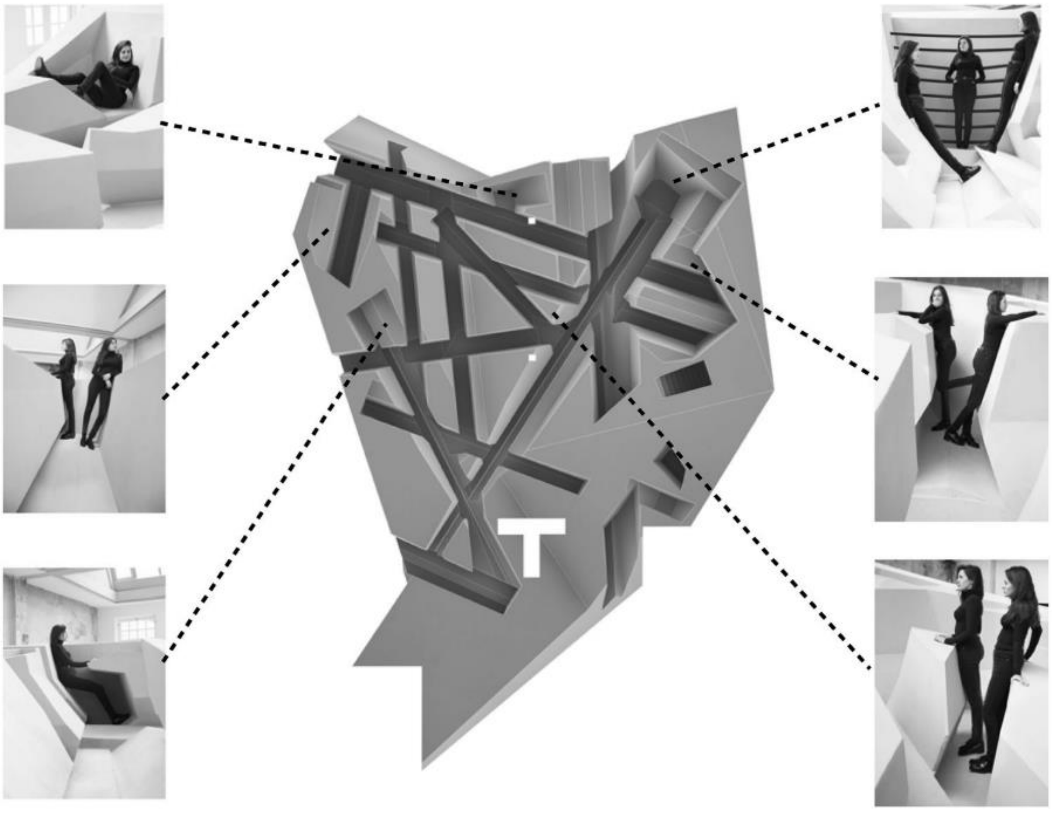

Figure 2.4: The end of sitting as presented by Withagen and Caljouw (2016)

2.4.2 Inviting safer locomotor behaviours

Although examples from environmental design (e.g., the end of sitting) evidence that body-size related affordances can invite specific behaviours, authors have suggested that the soliciting nature of affordances is influenced by organismic factors, including action capabilities (Rietveld & Kiverstein, 2014; Withagen et al., 2012). For example, Warren and Whang (1987) studied the visual guidance of walking through apertures. The authors determined that the ratio of aperture to shoulder width at the moment actors started rotating their body to avoid contact was greater than 1 (specifically 1.3) meaning body rotation was not needed. Thus, body dimension did not exclusively determine action (see also: Oudejans et al., 1996). Pertinent to adaptive locomotion, Konczak, Meeuwsen, and Cress (1992) showed that leg strength and joint flexibility, rather than body dimensions such as leg length (Warren, 1984), explained the affordance of maximum stepping height. Accordingly, these factors are important to consider throughout locomotor tasks where both body size and action capabilities have been shown to influence behaviours (Konczak et al., 1992; Warren, 1984).

In adaptive locomotion research, studies have evidenced that environmental design can invite behaviour adaptations (Zietz et al., 2011). For example, research focusing on stair based locomotion, has shown that visual interventions such as high contrast demarcation lines positioned on step edges can invite safer adapted behaviours (Foster et al., 2014; Iwata & Kitamoto, 2019; Thomas et al., 2021; Kim, 2009; Zietz et al., 2011). Moreover, the behavioural adaptations solicited have also been shown to differ between younger and older adult age groups. For example, Zietz and colleagues (2011) evaluated the effect of high or low contrast stair edges on the movement kinematics of younger, older low fall risk, and older high fall risk adults. Their findings showed that in the high contrast condition younger adults increased the horizontal distance between foot and step edge, low fall risk older adults positioned the COM towards the anterior, and high fall risk older adults reduced vertical COM variability. These findings led to the conclusion that in high risk older adult populations, high contrast edges invited adaptations associated with measures of posture and balance. Together, findings from stair based locomotion research and the end of sitting office highlight that when interacting with the same physical environment, behaviours differ as a factor of both body size and action capabilities. These findings indicate that invitations for action may be relational to action capabilities (Rietveld & Kiverstein, 2014; Withagen et al., 2017, 2012).

2.5 Moving surfaces as a paradigm for adaptive locomotion

The number of people living in urban environments is increasing. By the year 2050, 65% of the human population is predicted to be living in urban environments (United Nations, 2018). Incidentally, if current trend continues, more urban areas will be created during the first 30 years of the present century than across the totality of human history (Kaaronen & Rietveld, 2021). In addition to increased population density in the environments that humans inhabit (Mcgranahan & Satterthwaite, 2014), the composition of the human population is changing. This change has been linked to what has been termed a ‘longevity revolution’ (Unitied nations, 2019). Specifically, the human population is ageing. As of 2019, 1 in 11 people in the world was over 65 years old, yet by 2050 this is due to increase to 1 in 6 (United nations, 2019). Thus, it is feasible that greater numbers of older people will encounter the locomotor challenges associated with modern day urban living. In this case, it is also feasible that the frequency of incidents occurring as people fail to overcome environmental demands may also increase. Although research has begun to explore perceptual-motor behaviours when overcoming locomotor challenges (e.g., Matthis et al., 2018), the tasks and environments sampled by such research draw closely from locomotor pointing literature (e.g., Lee, et al., 1982) and have been noted as being distinct from common daily tasks (van Andel et al., 2018a).

Moving surfaces, such as escalators and travellators reflect a commonly encountered feature of urban environments. Occupying the same space as a conventional stair case, escalators have the capacity to move much larger numbers of people and have been noted as being the only viable option for high volume pedestrian transportation (Davis & Dutta, 2002). As such, escalators are used in a wide range of publicly accessible locations such as commercial buildings, department stores, and railway stations. However, there use is not without risk (Beards et al., 2022). Specifically, falling when transitioning between the static walkway and moving escalator surface has been recognised as causing injury to adults of all ages, however, incidents occur more frequently in older adults (>60 years; Schminke et al., 2013). Despite being identified as an area of increased fall risk, only one empirical study has explored young adults behaviours when stepping onto moving surfaces (Hsu et al., 2015). Therefore, research examining the perceptual-motor behaviours of older adults when stepping onto escalators (moving surfaces) has yet to be undertaken. Furthermore, although design interventions including high contrast demarcation lines and foot targets have been applied to escalators to invite safer behaviours (CIBSE, 2015; d2e, 2018), the impact of these interventions has yet to be tested.

Based on the aforementioned points pertaining to increased age and urbanisation, there is a clear need to understand how older adults negotiate urban locomotor challenges. Moreover, little research has explored adaptive locomotion or the effectiveness of design interventions through the lens of Fajen’s (2005, 2007) affordance based control. In the chapters to follow, this thesis will describe and justify the methodological approaches taken throughout subsequent chapters which examine how action capabilities and environmental demands may influence adaptive behaviours as pedestrians negotiate moving surfaces.

CHAPTER 3: SELECTION OF METHODS

This chapter describes and justifies the methodological approaches undertaken in the laboratory-based experiments presented throughout chapters 5, 6, and 7. Specifically, this chapter provides details of the participants tested, the design of the laboratory environment, as well as kinematic and gaze data collection and analysis protocols that were common throughout the subsequent experimental chapters. The chapter is comprised of the following parts: (3.1) Participants; (3.2) The design of the laboratory environment; (3.3) Procedure; (3.4) Kinematic data collection and analysis; (3.5) Gaze data collection and analysis; and (3.6) Statistical analysis.

3.1 Participants

Participants were recruited from the University and local (Portsmouth, UK) community. Ethical approval (Appendix 1 & 2) was granted at an institutional level with all participants providing informed consent. All participants completed a health history questionnaire, which established that they had no falling history, physiological, or neurological impairment prior to data collection.

Research has established that older adults use different (maladaptive) behaviours to overcome environmental challenges, and often fail to achieve the same level of successful locomotion as younger adults (Chapman & Hollands, 2007). The emergence of maladaptive behaviours identified in older adult age groups has been associated with the reductions in cognitive and physical (e.g., action) capability associated with the aging process (Maidan et al., 2018; McCrum et al., 2017; Roos et al., 2010; Uiga et al., 2015; van Andel et al., 2018b).

Table 3.1: Age related differences reported in extant research

Author (year)	Age group classification	Key findings
Schminke et al., (2013)	Hospitalised escalator users >16 years	Injuries predominantly caused by falls; Adults > 60 years old accounted for majority of incidents recorded.
Frimenko, Goodyear, & Bruening, (2015)	Meta analysis, non-pathological gait in adults >18 years	Measures of gait speed and step length exhibited a plateau between 20 and 40 years of age followed by gradual age related decline.
Chapman & Hollands (2006)	Younger adults (21-25 years) Older adults (27 – 76 years)	Older adults require visual information at specific times in order to utilise feed-forward control.
Ellmers, Cocks & Young (2020)	Older adults (>60 years) categorised by high or low fall risk.	High fall risk older adults exhibited gaze behaviours which prioritized proximal locations.
Roos, McGuigan, & Trewartha, (2010)	Younger adults (20-35 years) Older adults (65-75 years)	Insufficient recovery limb strength, response time and movement speed meant older adults adopted less demanding behaviour adaptations.
van Andel, Cole, & Pepping (2018)	Younger adults (19-33 years) Older adults (61-86 years)	Older adults produced shorter steps. Perceptual-motor coupling is related to action capability decline.
Caetano et al., (2016)	Younger adults (< 35 years) Older adults (> 65 years)	Older adults exhibited slow, short steps with reduced accuracy and increased error.
Alcock, Vanicek, & O'Brien (2013)	Older adults (60-83 years)	Advanced age related to reduced walking speed and altered gait kinematics such as reduced stride lengths and foot clearance.
St George, Fitzpatrick, Rogers, & Lord (2007)	Younger adults (23-40 years) Older adults (75-86 years)	Older participant groups had significantly increased stepping error, obstacle contact, and balance transfer times
Skervin et al., (2021)	Younger adults (18-29 years) Older adults (60 – 83 years)	Visual illusion on stairs led to increased foot clearance and perceived step height in older adults.
Thomas et al., (2021)	Younger adults (18-35 years) Older adults (low and high fall risk, both >65 years)	Stair edge highlighters sped-up decent in high risk older adults and increased foot clearance in younger and high risk older adults.

Despite different adaptive locomotor behaviours being well documented between younger and older adult age groups (for a review see Kovacs, 2005), there appears to be some disparity regarding the age ranges that are used to group younger and older participant cohorts in extant literature (Table 3.1). Capturing this issue, Alcock et al. (2013) noted that adaptive locomotor research typically classified younger adults as being between 20-40 years and older adults being aged between 55 and 80 years. Based on these age ranges and in an attempt to align with the common age ranges used in extant literature (Table 3.1), this thesis classified younger adults as being aged between 18 and 40 years and older adults as being older than a minimum age threshold of 60 years. Furthermore, this latter age-range was also commensurate with research highlighting a notable increase in injury frequency associated with stepping onto a moving surface (an escalator) in adults aged 60 years and over (Schminke et al., 2013).

As different adaptive locomotor behaviours have been identified between younger and older adult age groups (e.g., Table 3.1), consistent with the affordance based control (Fajen, 2005) account outlined in Chapter 2, one might expect that differences in locomotion could be reconciled by changes in action capabilities between these age groups. Throughout affordance based control literature, action capabilities have been established by asking participants to perform maximally, to establish the limits of their action boundaries (e.g., Dicks et al., 2010; Seifert et al., 2021). However, given that the moving surface paradigm developed in this thesis (see Section 3.2, below) simulates a setting that can lead to injuries, particularly in older adults (Schminke et al., 2013), it was deemed inappropriate to adopt a similar “maximal” approach, which may put participants at risk. Therefore, difference in the action capabilities of younger and older adults were inferred through the use of self-report measures of movement, which have established a relationship between increased maladaptive perceptual-motor behaviour and an increased fear of falling (Ayoubi et al., 2015; Chapman & Hollands, 2007; Ellmers, Cocks, & Young, 2020; Young & Mark Williams, 2015). As such, a questionnaire battery based on previous locomotor research was included to gain understanding of the differences between the two participant age groups. The questionnaire battery comprised of: (i) The Falls efficacy scale international (FESi), to provide a measure or fear of falling (Yardley et al., 2005); (ii) The

Activities Balance Confidence scale (ABCs), as this has been noted as more suitable to detect the loss of balance confidence in higher functioning older adults (Powell & Myers, 1995); and (iii) the Reinvestment scale (Masters et al., 2005), as higher fall risk individuals have been associated with a higher level of conscious attention to their own movements (Ellmers et al., 2020).

As will be elaborated in Chapter 5 to 7 in this thesis, the results from the questionnaire battery revealed that there were differences in self-report measures between the two age groups. Specifically, FESi scores in Chapters 5 to 7 reveal that older adults exhibited greater fear of falling than younger adults (Tables 5.1 & 7.1), whereas in Chapters 5 and 6, older adults ABC scores indicated a greater loss of balance confidence compared to younger adults (Table 5.1). These findings indicate that across Chapters 5 to 7, older adult participants exhibited greater fear of falling than younger adults, supporting the use of age boundaries as a method of grouping participants as well as confirming differences in action capabilities between the two age groups.

3.2 The design of the laboratory environment

van Andel, Cole, and Pepping (2018) have acknowledged that literature has predominantly evaluated human behaviour during tasks that do not sample day-to-day challenges, such as negotiating obstacles (Marigold et al., 2006), or intercepting moving targets (Fajen & Warren, 2004). However, it has been suggested that experimental settings, which examine only very specific aspects of human behaviour (e.g., targeted stepping movements) may not represent how people overcome the diverse challenges encountered throughout daily activity (Lappi & Mole, 2018; van Andel, Cole, & Pepping, 2018). In addition, it has been argued that experimental paradigms have been utilised in order to incorporate laboratory equipment such as visual occlusion, treadmills, or virtual reality systems, which may limit the generalizability of the setting studied (van Andel et al., 2018a). Together, these points suggest such approaches may be limited because they do not accurately sample the natural environment (Brunswik, 1956; Davids et al., 2006; Dicks et al., 2009). Reinforcing this suggestion, contemporary perspectives in ecological psychology have suggested that human behaviour is relational to a person's environment (Kiverstein et al., 2019; Rietveld & Kiverstein, 2014; Withagen et al., 2012, 2017). Likewise, empirical findings show behaviours are altered by environmental demands (Huys & Beek, 2010; Matthis et al., 2018). Together such points highlight the need to accurately sample human behaviour within an environment that accurately captures the demands of the 'real world' setting. Consequently, designing a laboratory environment that accurately represents the natural environment that experimental findings are intended to generalize towards is of paramount importance. Given that the overall aim of this thesis is to examine the perceptual-motor behaviours that underpin successful locomotion as younger and older adults negotiate the challenge of stepping onto moving surfaces, and subsequently explore the use of environmental design as a means of soliciting behaviour change, it follows that it is of importance to design an experiment that is characteristic of this setting.

In moving surface environments, most injuries are associated with falling as pedestrians transition between static and moving surfaces, such as when stepping onto an escalators moving surface (Beards et al., 2022; Hsu et al., 2015; Schminke et al., 2013). The heightened injury rate associated with moving surface environments (e.g., escalators) indicate that stepping between static and moving surfaces presents a challenge to successful locomotion. Moreover, the demand to accurately position the foot onto the moving surface (e.g., to avoid the boundary between steps) may further the challenge for older pedestrians (Beards et al., 2022). Indeed, this is particularly the case for escalators – in comparison to travellator, for instance – where it is necessary to place the feet accurately between demarcation lines that differentiate the moving steps before they separate. Accordingly, the focus when designing the laboratory environment was to accurately sample (simulate) the transition between the static approach surface and the moving surface. As a similar lab environment was used throughout all experiments in this thesis, this section describes the steps taken to develop the testing setting. Firstly, details of the moving surface element will be provided, including a pilot study explaining the use of markings. Secondly, details around the approach walkway will be provided.

3.2.1 Sampling a moving surface environment

Despite conversation with various organisations, it was impossible to source an actual escalator. Ultimately, this was because escalators are paramount to pedestrian flow and utilised to ease congestion in high foot traffic areas, meaning collecting data as pedestrians negotiated a ‘real life’ escalator may hinder public safety. Moreover, manipulating characteristics of the escalator belt or walkway required qualified engineers to carry out an assessment with every experimental condition change, vastly increasing the time required to carry out testing. Furthermore, due to technical complexity, cost, and restricted laboratory space, constructing a replica escalator was not possible. However, escalator design is governed by European standard EN115. In terms of designing a lab environment, the fact that the environment is determined by the standard, ensures that the requirements can be followed to sample aspects of the escalator setting. In line with these standards, escalators are characterised by a moving surface that commonly travels at speeds of 0.50m.s^{-1}. Escalators are typically 1m wide and divided horizontally by steps 0.38m deep (CIBSE, 2015). When transitioning onto the moving surface, pedestrians’ step onto a flat moving surface, which separates vertically to form steps shortly after embarkation (2-5 step lengths; 0.76m - 1.90m). The location of step separation in relation to incidents occurring suggests the change in step height may not play a major role in pedestrian falls (Beards et al., 2022). Therefore, this was not a component of the environment I wished to sample. Further, as this thesis was chiefly concerned with locomotor adaptation. Based on these characteristics a 1m wide and 3m long conveyor belt, which could be set to travel at a range of speeds, was selected to replicate the escalators moving surface (CIBSE, 2015; Figure 3.2).

Step boundaries on the moving surface

When stepping onto an escalator, research has suggested that participants adapt their gait to avoid stepping on the boundaries between steps (Beards et al., 2022; d2e, 2018). Accordingly, the presence of boundary lines on the moving surface are considered an element of the escalator environment that must be sampled. Despite consistent step dimensions, as governed by design standards, the use of high contrast demarcation lines (which are often painted onto the step's leading horizontal edge) are at the discretion of the operator and therefore inconsistently applied (CIBSE, 2015). This inconsistency has produced a disparity where step boundaries, can be either 'high' or 'low' contrast with the escalator surface (d2e, 2018).

Although high contrast step boundaries have been recognised as an intervention that may improve user safety (CIBSE, 2015), literature on this topic is limited (Cohen & Sloan, 2016). A literature search, correspondence with the Health and Safety executive (HSE, 2018), and external consultancy (d2e, 2018) identified no empirical research specifying the characteristics of demarcation lines or validating the use of demarcation lines as an effective intervention on escalators. To accurately sample the performance environment (as per Chapters 5, 6 and 7) and to allow the comparison of high and low contrast demarcation line conditions (as per Chapter 6), literature detailing adaptive locomotion outside of the escalator context was considered (Thomas et al., 2021; Zietz et al., 2011). Public building regulations (British Standards Institution, 2018) state that, on staircases, a minimum 30-point light reflectance value difference between demarcation lines and the stair step surface must be present to signify a contrast. As the research in this thesis is specific to public settings, a 30-point difference between surfaces was recognised as an appropriate threshold to establish a high contrast between belt surface and demarcation line. A pilot study was required to establish if the lines added to the conveyor belt surface were sufficient to meet these requirements.

Step boundary line contrast pilot study

The boundary lines between escalator steps are an important aspect of the performance environment. As such, it is important to establish the properties of the demarcation lines used in the experimental chapters of this thesis. In Chapter 6 the influence of high and low contrast demarcation lines positioned on the belt surface will be evaluated, highlighting the need to identify conditions that are classified as high or low contrast. This pilot study aims to establish whether two different materials (Green and White coloured self-adhesive tape, based on the colour of conveyor belt surface) could be used to create high and low demarcation lines.

Spot luminance measurements were taken to examine whether the tape representing high and low contrast demarcation lines positioned on the moving surface were sufficient to be classified as having a high or low contrast to the belt surface. Luminance measurements were taken from the position of an approaching pedestrian, 1m away from the belt surface, using a calibrated Minolta SL110 Luminance meter. In line with standard procedure, five recordings were taken per condition with a 30-point difference used to quantify a sufficient contrast between conditions (British Standards Institution, 2018; GAI Guide to Standards, 2016)

Table 3.2: Mean light reflectance values (LRV) for conveyor belt and demarcation lines

Condition	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean
Belt surface	5	4	3	5	4	4.2
Green tape	19	17	17	18	17	17.6
White tape	35	35	34	34	36	34.8

Table 3.2 shows a 13.4 point difference between the belt and low demarcation line and a 30.6 point difference between the belt and high contrast demarcation line light reflectance

values. Taking building regulations (British Standards Institution, 2018) as a guideline, the readings between the belt surface and the green and white taped lines were sufficiently different to be categorised as low and contrast respectively. Based on these results, the materials were used to create step boundaries on the belt surface (e.g., Figure 3.2).

3.2.2 The approach walkway

Following the arrangement of a moving surface that represented an escalator, an approach to the moving surface was required. Perceptual-motor control research has commonly reported that behavioural adaptations emerge throughout the strides preceding a target or obstacle (Barton et al., 2019; Higuchi, 2013a; Lee et al., 1982). Furthermore, manipulating the approach to a location has been recognised as influencing locomotor behaviours (Cinelli & Patla, 2008; Higuchi, 2013; Matthis & Fajen, 2014). These findings highlight the importance of designing an approach to the moving surface that captures the demands associated with stepping onto moving surfaces.

The smooth join between an escalator and approach walkway is achieved through the use of a comb plate and raised ridges along the escalator’s moving surface. As previously alluded, due to technical complexity, cost, and restricted laboratory space, constructing a replica escalator was not possible. As an alternative, the height of the walkway (Figures 3.1 & 3.2) was designed to match the height of the conveyor belt surface and provide a flat, level, approach which alleviated gait inconsistencies induced through changing surface height. To achieve this, the front edge of the walkway was bevelled to match the circumference of the conveyor belts tail pulley, allowing the walkway surface to sit flush with the conveyor belt surface (Figure 3.1). A walkway length of two meters was selected based on discussions with the health and safety executive (HSE), the government regulatory body who oversee the design and maintenance of public environments, and vertical transportation consultants (d2e, 2018). This distance recognised that when alighting a moving surface in everyday settings, unconstrained long approach distances are often infeasible. For example, when using an escalator people are commonly first required to negotiate other pedestrians or baggage preventing barriers. From a locomotor research viewpoint, a distance of two meters is also consistent with approaches to targets in previous research (Chapman & Hollands, 2006b; Uiga et al., 2018).

Figure 3.1: The join between walkway and belt surfaces.

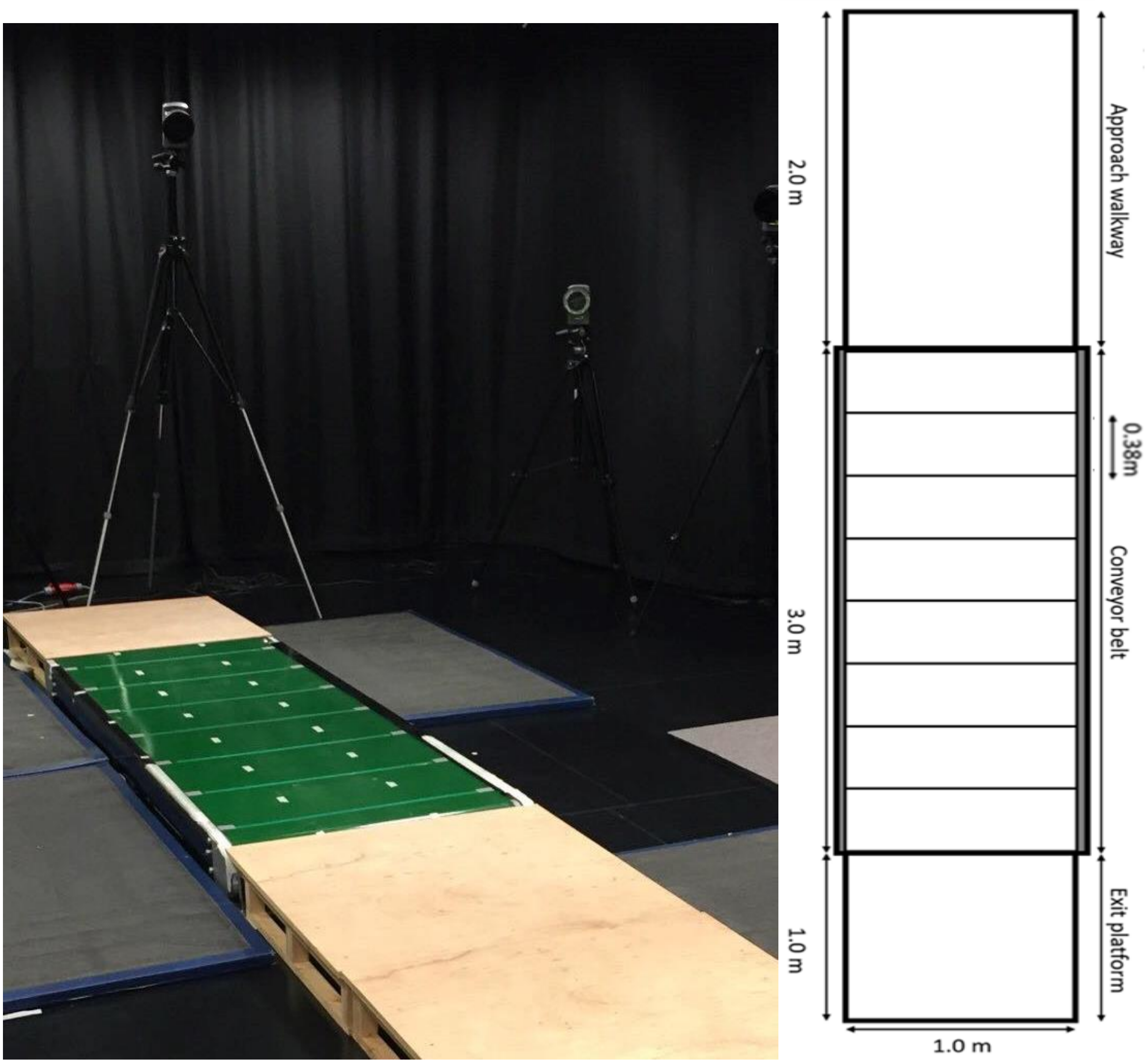

Figure 3.2: An overview of the lab environment. Left: In this image the conveyor belt is set up to present low contrast demarcation lines with high contrast foot targets, as considered in Chapter 6. Right: an overview of the lab set up highlighting dimensions in experimental Chapters 5, 6, and 7.

3.3 Procedure

Following the design of an environment, which as closely as possible simulated the initial flat portion an escalator, prior to the tread steps separating, a a protocol was devised that aimed to study adaptive behaviours that would be consistent with those utilised by people when stepping onto such moving surfaces (CIBSE, 2015). Consistent throughout all experimental chapters, participants completed 10 trials in each experimental condition (Marigold & Patla, 2008; Thies, Richardson, & Ashton-Miller, 2005). In each chapter, the order of experimental conditions (e.g., Chapter 5 compared four experimental conditions: static and moving surfaces; with and without demarcation lines) were randomised per participant with participants resting for a minimum of 5 minutes between conditions (e.g., blocks of 10 trials) to reduce the effects of fatigue (Dingwell et al., 2017; Thompson & Franz, 2017).

Participants started each trial with their heels touching the rear edge of the approach walkway and following a ‘go’ signal from the experimenter, walked along the two-metre walkway at a self-selected pace, before stepping onto the conveyor belt and then standing stationary on the belt surface until the end of the trial (total trial duration lasted approximately 8 seconds). To promote a natural gait pattern, the leading foot used to step onto the belt was not regulated. Recognising that unlike an escalator, demarcation lines representing step boundaries would not separate vertically, participants were instructed to avoid contact with demarcation lines positioned on the conveyor belt surface. In experiments where high or low contrast demarcations were presented, the experimenter’s instructions remained consistent. Likewise, in experiments where foot-targets were presented to participants (Chapter 6 & 7; Figure 3.2), the experimenter did not highlight any change to the environment’s visual properties. That is to say, participants were not informed how to behave relative to these changing environmental features.

3.4 Kinematic data collection and analysis

Following the design of the experimental setting, which represented stepping onto an escalator, a method that allowed the capture of participant behaviours in this environment was required. In particular, the thesis aimed to measure the adaptive kinematic behaviours that underpin successful performance (Bruijn & Van Dieën, 2018). Based on these requirements, kinematic data were collected using optoelectronic motion capture (Oqus 300/310, Qualisys Sweden). Optoelectronic systems are often regarded as the gold standard in motion capture in terms of measurement accuracy and have become one of the most commonly used systems for measuring human kinematics (van der Kruk & Reijne, 2018). Moreover, as measurements are mapped to a laboratory co-ordinates, optoelectronic systems are capable of capturing the precise temporal-spatial location of person-environment interactions, such as foot placements, with a world-space frame of reference.

3.4.1 Apparatus

Fourteen optoelectronic cameras (Oqus 300/310, Qualisys Sweden), sampling at 100Hz encircled the approach and treadmill areas (e.g., Figure 3.2). This sampling frequency was selected based on extant adaptive locomotor and gait research (Winter, 2009). An area (5x1x2m, x,y,z dimensions respectively) was dynamically calibrated with marker deviation upper limit of 1.48mm applied to promote accuracy (Summan et al., 2015). Participants were instrumented with spherical retro-reflective markers (12mm diameter). Collectively these markers enabled body segments to be modelled following C-Motion (2018a) guidelines (Figure 3.3). The markers were placed bilaterally on: anterior superior iliac spine, posterior superior iliac spine (as per ‘CODA pelvis’); femur greater trochanter, femur medial condyle, femur lateral condyle (as per ‘Thigh model 1’); tibia medial malleolus, tibia lateral malleolus (as per ‘Shank model 1’), base of 2nd metatarsal, base of 5th metatarsal and calcaneal tuberosity (as per

‘Foot segment 1’). A further four cluster markers were attached to the lower limbs with elasticated straps located on the thigh midway between the greater trochanter and lateral condyle of the femur and on the shank midway between the lateral condyle of the femur and the lateral malleolus. The dimensions of each participants footwear were also recorded to ascertain distance between end of footwear and start of moving surface.

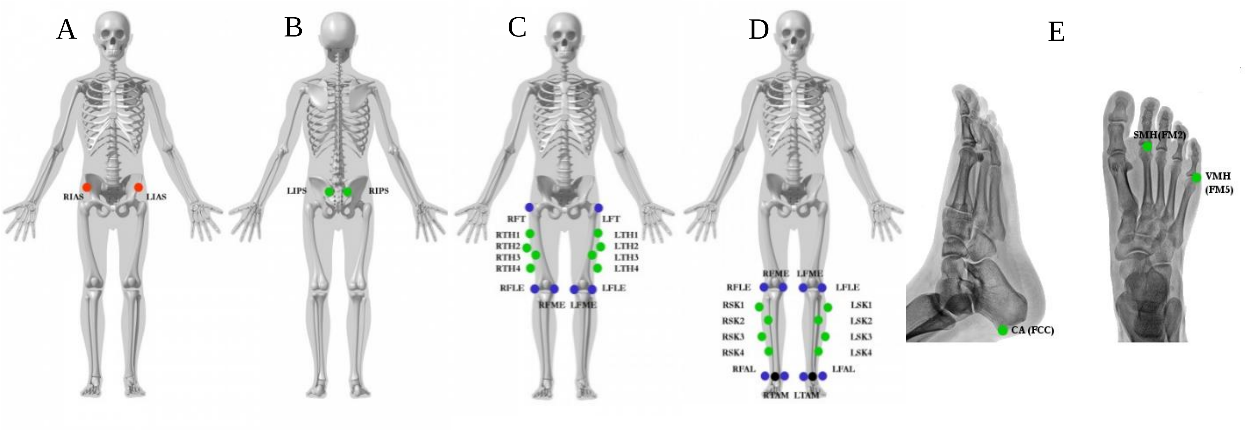

Figure 3.3: Retroreflective marker positions used for optoelectronic motion capture. A and B show markers for CODA Pelvis; C shows markers for Thigh model 1; D shows markers for Shank model 1; E shows markers for Foot segment 1.

3.4.2 Signal processing and event detection.

As per previous research (Chapman & Hollands, 2006b; Domínguez-zamora et al., 2020; Luo et al., 2021) and consistent with best practice for gait data (Winter, 2009), all raw kinematic data were passed through a 4th order low pass Butterworth digital filter at a cut off frequency of 6Hz prior to model building and analysis. A CODA Pelvis model was then created using Visual 3D (C-Motion, 2018b). Key gait events (foot contact and toe off) were identified. The use of horizontal heel displacement to identify heel strike is prevalent throughout over ground walking tasks (Banks et al., 2015). However, because this technique is dependent on the maximum displacement between contralateral heels to identify foot contact, the act of alighting a moving surface rendered it inappropriate as displacement was influenced by the moving surface. Instead, foot contact was identified utilising the vertical acceleration of heel and toe markers (Hreljac & Marshall, 2000). Position and velocity data for the pelvic centre of mass (COM) in the anterior posterior direction, as well as penultimate step and final step times and positions were exported for analysis in MATLAB (MathWorks Inc, 2019).

3.4.3 Kinematic variables

Based on the limited research exploring people's behaviours as they step onto moving surfaces (Hsu et al., 2015), variables commonly considered throughout the wider adaptive locomotion literature base were considered. Perceptual-motor control literature pertaining to adaptive locomotion has identified that a synergy of online and feed-forward control behaviours are utilised to achieve successful locomotion (Barton et al., 2019). Broadly, feed-forward and online behaviours are described as adaptations that occur through the approach and concurrent movements, respectively. Therefore, variables that captured behaviours throughout both the approach phase and the event when participants stepped onto the conveyor belt surface (e.g., the final step) were selected. A description of each variable is included in the following sections. The amount of variability has been suggested to reflect maladaptive locomotion (Hausdorff, 2005) especially in older adult age groups (Kovacs, 2005). Although many measures of variability exist, a review of measures assessing the stability of locomotion (Bruijn et al., 2013) identified that standard deviation is the dominant measure of variability. Therefore, comparable with adaptive locomotor literature, variability measures throughout this thesis were calculated using one standard deviation of step length, step time, toe distance and approach time, across each experimental condition (Bruijn et al., 2011, 2013; Maki, 1997; Zietz et al., 2011).

Perturbation Magnitude

As successful locomotion is a recurring theme across all experiments, a measure of successful locomotion able to capture the environmental demands posed by the various experimental conditions was required. When negotiating challenging environments such as rough terrain, successful locomotion is defined by the ability to adapt to the increased demand on balance, which is thought to be achieved by primarily reducing prospective gait perturbations (Higuchi, 2013; Wu, Brown, & Gordon, 2017). That is, perturbations have been conceptualised as movements that deviate from steady state patterns (Bruijn et al., 2013) and occur when either task demand, or when an internal or external force requires the individual to maintain balance (Wu et al., 2017), change direction (Bastin et al., 2010), or adapt movement patterns (Fajen & Matthis, 2011). However, direct measures of successful locomotion, or perturbation, in rough terrain contexts are uncommon, with locomotor research often favouring comparisons of spatiotemporal stride variables to capture the effects of environmental demand (St George et al., 2007; van Andel et al., 2018a; See also: Matthis et al., 2014 and McAndrew et al., 2012). The following section presents the methods used to measure successful locomotion (e.g., perturbation magnitude) throughout this thesis.

Adaptive locomotion, and in particular anticipatory adaptations, are centralised around minimising the extent the environment perturbs stable, efficient, locomotion (Higuchi, 2013a; McCrum et al., 2017). Further, successful locomotion has been characterised by a person’s ability to overcome environmental challenges and reduce the environment’s impact on locomotion (Donelan, 2016). Based on these definitions and drawing inspiration from Fajen and Matthis (2011) work, which aimed to investigate the perception of affordances in relation to the individual’s movement capabilities by examining adaptive behaviours in relation to the minimum velocity[4] required to pass through an aperture before it closed to a dimension less than minimum body width; a method was developed to quantify successful locomotion based on perturbation from a ‘smooth’ unaltered approach.

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[4] The measure of minimum velocity was defined as the distance the individual must travel to pass through the aperture, divided by the amount of time remaining until the gap reaches a size at which it is no longer passable.

Within targeted locomotor research the goal or target is often an isolated event, for example, an aperture is either passable or not (Cinelli & Patla, 2008; Fajen & Matthis, 2011); a fly ball is catchable or out of reach (Postma et al., 2017), or the braking strength of a motor vehicle is either sufficient or inadequate to avoid a collision (Fajen, 2005a). In contrast, alighting a moving surface with numerous steps presents multiple opportunities for success. As such, consideration of a minimum velocity-based threshold determined by the moment, or boundary, a goal becomes unachievable is not appropriate when considering how people successfully step onto moving surfaces. Alternatively, the calculation of the mean velocity required between gait initiation and foot contact with the belt surface to allow an unperturbed 'smooth' COM trajectory to be extrapolated. Specifically, the approach adopted in the current work was to compare the extrapolated unperturbed trajectory with the actual COM trajectory on each trial. This approach allowed behaviour adaptations to be measured relative to an unperturbed trajectory that considered the least anterior-posterior deviation from the moment the participant initiated gait until the moment of alighting the moving surface. Relevant to locomotor control, the peak deviation from this trajectory can provide insight into the behaviours that enabled stepping onto the moving surface. For instance, research pertaining to the prospective control of movement suggests that control based on the coupling of perception and action will not result in adapted behaviours, unless the need for an adjustment is perceived (Montagne et al., 2000b). Therefore, smaller peak perturbation magnitudes would be indicative of participants adapting their approach to transition onto the moving surface (e.g., Figure 3.4 A). Alternatively, a large perturbation (e.g., Figure 3.4 B) may be observed if a participant pauses before initiating the step onto the moving surface, such a behaviour would be consistent with 'hesitation' identified in older escalator users (Beards, et al., 2022; d2e 2018). Such behaviour would result in a large perturbation magnitude and may result if a participant prioritised proximal stepping constraints (e.g., Ellmers et al., 2020) effectively treating the approach walkway and step onto the moving surface as two distinct tasks.

In order to calculate perturbation magnitude, the processed anterior-posterior position and velocity data for the pelvic centre of mass (COM) as well as time and position of the foot contact with the conveyor belt surface were exported for analysis in MATLAB. To alleviate the inconsistencies caused through gait initiation (Matthis & Fajen 2009), the approach phase was defined as the period of time between the participant's gait initiation and the participant's initial foot contact with the conveyor belt surface. Gait initiation was identified based on previous research considering younger adults, older adults and Parkinson's patients (Halliday, Winter, Frank, Patla, & Prince, 1998). Halliday and colleagues, utilised a 10 second quiet standing task, after which participants initiated gait prompted by an auditory cue. Gait initiation was recorded via force plate and was classified as the point of maximum medial shift of the centre of pressure toward the first stance limb. This was labelled 'unload' and within the gait cycle corresponded to toe-off of the first swing limb (Halliday et al., 1998). The authors reported COM velocities of 0.50m/s and 0.63m/s at unload for older and younger participants respectively. Accordingly, gait initiation for all participants was classified as the moment that COM velocity exceeded 0.50 m/s. The approach phase terminated with the COM location at time of foot contact with the belt surface.

Following identification of the approach phase and building on the minimum velocity concept outlined by Fajen and Matthis (2011), the anterior – posterior distance of the approach phase for each trial was divided by the approach phase duration. Calculating minimum velocity allowed a predictive, linear COM trajectory to be extrapolated (Figure 3.4). For each frame throughout the approach phase, the absolute distance between the actual pelvic COM position and the extrapolated unperturbed trajectory position was calculated. The peak value per trial was identified and taken as a measure of perturbation magnitude (Figure 3.4).

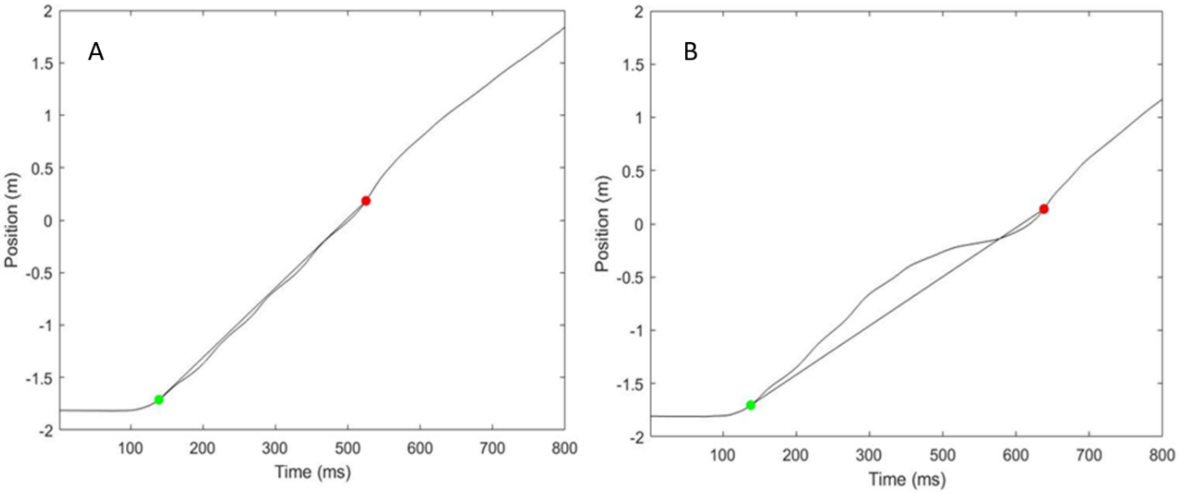

Figure 3.4: Examples of different perturbation magnitude measures taken from a single participant's approach phase. Both Figure panels are from trials where the participant transitioned onto a moving surface. Green markers represent pelvic COM location at gait initiation and red markers represent pelvic COM location at foot contact with the moving surface. Left (A) shows a relatively unperturbed approach (perturbation magnitude measure of 0.07m); Right (B) shows a relatively perturbed approach (perturbation magnitude measure of 0.31m).

Step Length

Step length was calculated as a measure of the anterior-posterior distance between the retroreflective markers positioned on the calcaneal tuberosity at the final footstep on the walkway and at foot contact with the moving surface (Hsu et al., 2015). It should be noted that step lengths on flat obstacle free terrain differ depending on an individual's leg-length. Accordingly, step length measures between age groups will be treated with caution when comparing between age groups (for example a younger adult group being on average taller, may naturally have a greater step length). Based on the repeated measures experimental design, step length can be used to compare behaviours between different experimental conditions, for example, contrasting the behaviours that underpin successfully stepping onto static and moving surface conditions (Hsu et al., 2015). In the literature, a reduction in step length has been associated with participants adopting a ‘cautious gait’, which describes a group of behaviours people adopt to promote stability when overcoming environmental demand (Kal & Ellmers, 2020; Lawrence et al., 2015; Marigold & Patla, 2008b; Reelick et al., 2009; Swart, Otter, & Lamoth, 2020; Thomas et al., 2020). Separately, reduced step length has been associated with reduced motor and cognitive capacity (Galna, et al., 2009; Maidan et al., 2018). Step length altering behaviours have commonly been interpreted as evidence that a metabolically demanding, online, perceptual-motor behaviour has been utilised to accurately guide the foot onto a target location or avoid an obstacle (Moraes et al., 2004; Weerdesteyn et al., 2004).

Step length variability was calculated as one standard deviation of the step length measurements recorded per condition. Increased step length variability has been associated with increased online control and commonly observed when people overcome challenging terrain (Matthis et al., 2017). Affirming the association with online control, research has established increased step length variability when participants step onto targets when visual information is limited to distances of less than two step lengths, a distance authors have noted as critical for exploiting the ballistic dynamics of the body to adapt movement using feed-forward control (Matthis & Fajen, 2012; Matthis, Barton & Fajen 2017).

Step Time

Step time has been calculated in previous research considering human adaptive behaviours when stepping onto moving surfaces (Hsu et al., 2015). Corresponding with this research, step time was computed as the duration between the last foot contact with the walkway and the first foot contact onto the belt surface. In the wider literature, reductions in step time have been associated with limiting the time spent in the gait cycle’s single support phase and, akin to step length adaptations, referred to as symptomatic of a ‘cautious gait’ (Kal & Ellmers, 2020; Lawrence et al., 2015; Marigold & Patla, 2008b; Reelick et al., 2009; Swart et al., 2020; Thomas et al., 2020). Further, age related reductions in step times, particularly when overcoming environmental challenges, have led to older adults movement being noted as more conservative (Chien et al., 2018; Kovacs, 2005; Marigold & Patla, 2008b; van Andel et al., 2018b).

Step time variability was calculated as one standard deviation of step time (Bruijn et al., 2013). An increase in step time variability is associated with frailty in older adult populations, which in turn has been accredited with increasing risk of falling (Kressig, et al., 2008; Kroneberg et al., 2019), and associated with increased conscious control of movement (Young & Williams, 2015). As such, increased variability in step time measures are indicative of increased online control (Hausdorff, 2005). Furthermore, consistent with this interpretation, research has shown that throughout gait, changes to step time are relational to adaptations in step length, thus presenting a means of accurately controlling concurrent movement to position the foot (Barton et al., 2017).

Toe Distance

Toe distance (cm) was measured as the anterior-posterior distance between the belt surface threshold and the front edge of the foot at the moment of the final step (as per: Madalena et al., 2018; Rietdyk & Rhea, 2006; Zietz et al., 2011). This was calculated using the supporting foot's calcaneus marker position, taken as the contralateral foot crossed the threshold between the end of the walkway and start of the belt surface (e.g., establishing the foot was mid-flight), and footwear length.

A reduction in lead foot to obstacle distance has been associated with a decrease in motor, cognitive and functional abilities (Maidan et al., 2018). A reduction in toe distance has also been recorded as participants overcome tasks of increased difficulty, particularly in studies using obstacles that may require large step length modifications (Weerdesteyn, Nienhuis, & Duysens, 2005). Based on this, reduced toe distance has been associated with an increased risk of a fall, particularly within older populations (Galna et al., 2009; Muir et al., 2015; Weerdesteyn et al., 2005).

Toe distance variability is comparable to measures of anterior-posterior foot placement variability for the penultimate step. The variability of the step preceding a locomotor challenge provides insight into how participants controlled their movement (Barton et al., 2017;Matthis et al., 2017). Researchers (van Andel, Cole, & Pepping, 2018) who have examined younger and older participants approaching and stepping onto a kerb found that participants mostly regulated their approach to achieve minimal variability in the foot placement on top of the kerb, rather than a placement in front of the kerb. Their results indicated that the influence of ageing was most pronounced at the end of the approach. Resultantly, the authors suggested that aiming for a low variability in foot placement in front of the step up might be reflective of a stronger coupling between perception and action in older adults. Moreover, locomotor-pointing research suggests that regulation of the footstep location preceding an obstacle enables people to manipulate the ballistic trajectory of their centre of mass (COM), thus efficiently controlling subsequent foot placement via feed-forward control (Barton et al., 2017; Matthis, et al., 2017). Consistent with van Andel and colleagues’ suggestion, increased feed-forward control has been associated with older adults and reported in research contrasting younger and older adults behaviours (Chapman & Hollands, 2007). Therefore, considering the variability in toe distance can provide an indication regarding the use of feed-forward or online control behaviours, with a reduction in variability being associated with feed-forward control.

Approach time

Approach time (s) was measured as the duration of the approach phase, which was classified as the period between movement start, which as extrapolated from research into older persons steady state walking speeds (Halliday et al., 1998), was identified as the instant pelvic COM velocity, was greater than 0.50 m.s^{-1} and ended with the foot’s initial contact with the belt surface. Measurements of approach time or approach speed are common throughout adaptive locomotion literature, where increases in approach time, or trial durations, have been noted in older compared to younger populations or between participants overcoming challenging compared to simple environments (Ellmers et al., 2020; Kovacs, 2005; Marigold & Patla, 2008b; van Andel et al., 2018b). Such studies suggest adopting a slower approach may present an important adaptation that not only promotes stability, but also alleviates concerns related to the fear of falling (Parr et al., 2020). Moreover, research concerning perceptual-motor control has positioned that by increasing approach time, participants are able to gather visual information and enhance environmental certainty, by prolonging search prior to committing their COM throughout future steps (Matthis et al., 2018; Muir et al., 2015). Based on these points, an increase in approach time may be indicative of increased feed-forward control.

Approach time variability was measured as one standard deviation of approach time (Bruijn et al., 2013). Previous literature has highlighted that increased variability is representative of behaviour adaptation (Hausdorff, 2005). Consistent with literature advocating that adapting movement throughout the approach to an environmental challenge is associated with prospective control (for a review see: Higuchi 2013), it was interpreted that an increase in approach time variability may be symptomatic of feed-forward control (Barton et al., 2019; Matthis et al., 2018; Matthis & Fajen, 2014). Supporting this interpretation, if an individual's approach were entirely predictive, that is to say, without prospective adaptations, I would expect to observe low approach time variability (Katsumata & Russell, 2012).

3.5 Gaze data collection and analysis

Measuring gaze behaviour has expanded the current understanding of visually controlled action across a wide range of settings (Barton et al., 2017; Higuchi, 2013a). For instance, research exploring gaze behaviour throughout adaptive locomotor tasks has highlighted that people's actions are relational to both environmental demand (e.g., Matthis et al., 2018) and action capabilities (e.g., Chapman & Hollands 2007). Therefore, measuring gaze behaviours as participants overcome locomotor challenges will enhance our understanding of how people adapt to surpass environmental demand.

Within the field of perceptual-motor control, the accurate study of coordination between the eyes, head, and body has been hindered by the lack of suitable technology (Kothari et al., 2020). For example, determining point of gaze relative to environmental features has predominantly been achieved via mobile eye tracking. However, gaze data collected via mobile eye tracking is most commonly presented as point of gaze overlaid on scene camera footage (Hessels et al., 2020; Jongerius et al., 2021; Kothari et al., 2020). In turn, analysis of mobile eye data is often achieved through frame-by-frame approaches, where point of gaze is classified based on the amount of time a person's point of gaze is located on designated environmental locations (Ellmers et al., 2016, 2020; Mele & Federici, 2012; Parr et al., 2020). However, while mobile eye trackers deliver gaze data in a head-centred reference frame (e.g., with reference to scene camera position), for many research topics, such as adaptive locomotion, gaze data in a world-centred reference frame (e.g., within a laboratory coordinate system) can be considered beneficial (see: Matthis et al., 2018). Moreover, researchers evaluating eye tracking data analysis have suggested that scene based analysis methods are prone to inter-observer error and are considered time consuming (Duchowski, 2007; Kiefer, et al., 2017). As such a clear need to develop a method of capturing world-centred gaze data was identified. This need will be addressed in Chapter 4. However, it is appropriate to provide a justification of the gaze variables included throughout Chapters 5 – 7.

3.5.1 Gaze Variables

Look ahead distance

Research has shown that gaze allocation is relational to terrain complexity, revealing that as complexity increases, look ahead distance commonly decreases (Matthis et al., 2018). Matthis and colleagues suggested that the reduced look ahead distance measured in more complex settings occurred to ensure pedestrians maintained a degree of certainty regarding future movements. Moreover, research comparing the gaze behaviours of high and low fall risk older adults completing a locomoting pointing task reported that high risk participants prioritised attending to proximal areas when overcoming more threatening conditions (Ellmers et al., 2020). The authors suggested that attending to proximal gaze locations indicated diminished subsequent stepping performance, as participants ability to perceive and negotiate upcoming environmental hazards may have been impaired. Broadly, these findings and others (Kal & Ellmers, 2020) allude to a reduction of look ahead distance being associated with increased online control. Conversely, increases in look ahead distance has been associated with increased certainty of proximal environment, and anticipatory adaptation through feed-forward control. Therefore, look ahead distance provides understanding on the relationship between environmental demand and the visual control of action. Throughout this thesis, look ahead distance will be defined as the anterior-posterior distance (m) between the participant's eye and the participant's point of gaze location.

Walkway gaze transfer

Researchers (Barton et al., 2019; Matthis et al., 2018) have shown that the position of the step preceding a target or obstacle plays an important role in regulating the subsequent step's location. Importantly, studies exploring how people overcome environmental demand have identified that in conditions of increased terrain complexity, participants looked ahead (to subsequent step locations) earlier throughout the gait cycle (Ellmers & Young, 2019; Matthis et al., 2018). Moreover, in research comparing different age groups behaviours when overcoming sequential environmental challenges, earlier gaze transfer time away from proximal footstep locations has been observed in older adults compared to younger adults (Chapman & Hollands 2007). These results suggest that earlier gaze transfer times from the immediate foot-step location are associated with a reduction in concurrent stepping accuracy (Chapman & Hollands 2007; Domínguez-zamora et al., 2020). However, although concurrent stepping performance may decline, earlier gaze transfer has been suggested to ensure that individuals have enough certainty about the environment to commit their body's momentum towards future footstep locations (Matthis et al.,2018). Accordingly, an increase gaze transfer time (e.g., looking away earlier before foot contact) is indicative of feed-forward control behaviours, whereas reduced (e.g., looking away later before foot contact) gaze transfer times indicate online control of concurrent movement. As identification of these perceptual-motor control behaviours will be used throughout this thesis, the time spent attending to the step location prior to stepping onto the conveyor belt surface was measured. That is, walkway gaze transfer was measured as the time difference (ms) between the final foot contact with the walkway surface and the last time foveal vision was in the footstep area[5].

Belt gaze transfer

Research examining the differences between older and younger adults during sequential targeting tasks has commonly considered the time period between a participant looking away from a target and the foot making contact with that target location (Chapman & Hollands, 2006b; Young & Hollands, 2012). This research has consistently reported that older adults with increased risk of a fall transfer gaze away from the target earlier than younger adults. This finding has been associated with prioritising feed-forward control over online control

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[5] The footstep area was determined using location of the calcaneus marker throughout support phase and footwear dimensions.

(Chapman & Hollands 2006). Moreover, this behaviour has also been associated with greater anxiety and a shift away from the control of concurrent stepping movements (Ellmers & Young, 2019). Belt gaze transfer was measured as the time (ms) difference between the foot contact with the belt surface and the last time foveal vision was in the footstep area.

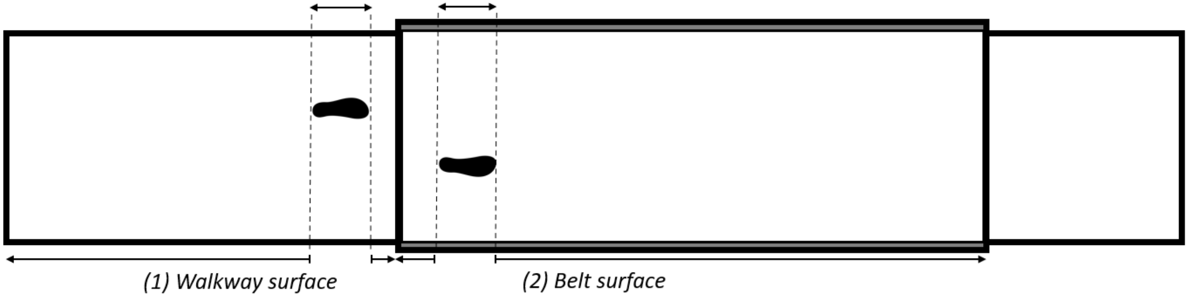
Area of interest analysis

People with reduced action capabilities and people performing in more challenging environments have been noted as adapting the locations they allocate gaze (Chapman & Hollands, 2007). For example, older adults have been found to increase obstacle viewing compared to younger adults when required to complete a simultaneous cognitive task, which has been associated with reductions to cognitive capacity (Domínguez-zamora et al., 2020). Further, in a sequential foot targeting task, Ellmers and colleagues (2019) reported that participants viewed the second foot target less under threatening conditions and prioritised areas of the walkway needed for online control. This result indicates anxious individuals prioritised success throughout current movements at the expense of performance when faced with subsequent constraints. Based on these findings, consideration of visual attention in relation to areas of interest (AOI) can provide valuable insight into perceptual-motor control. AOI analysis is commonly undertaken to consider how gaze is allocated within the participants environment during various aspects of daily life (Kurzhals et al., 2017).

AOI based analysis has been undertaken using a range of methods, with no standard procedure of how to collect, process, and analyse eye movement data being readily available (Vansteenkiste et al., 2015). One methodological divergence pertains to how visual attention is classified, with researchers either summing the amount of time a participants point of gaze was within a designated area (termed ‘dwell time’) or only considering fixations (the intervals between saccades in which gaze is held almost stationary and visual information is attained) within these areas (Land & Tatler, 2009). These separate approaches have been adopted in recent studies pertaining to perceptual-motor control during adaptive locomotion. First, Domínguez-Zamora and colleagues (2020) measured fixations on areas of interest, only counting periods greater than 66ms (identified between peaks caused by saccadic angular velocity). Alternatively, Hildebrandt and Cañal-Bruland (2020) applied a dwell time approach. The authors measured the percentage dwell time on different AOIs during the approach to a long-jump take-off board.

Research conducted by Vansteenkiste et al. (2015) compared dwell-time and fixation based AOI analysis approaches using data collected as participants cycled different routes. Findings suggested differences between the analysis methods and the authors suggested that in studies that involve dynamic movement, shorter data collection periods, or smaller AOI, fixation based approaches may not be adequate (Vansteenkiste et al., 2015). Furthermore, research identifying fixations has typically measured the duration that point of gaze remains stable on a single location, as classified by visual angle. However, the duration of this period varies in extant literature. For example, the periods of stable gaze that classify as a fixation include 66ms (Domínguez-zamora et al., 2020), 100ms (Ellmers et al., 2019), and 120ms (Wood & Wilson, 2010). The exact reasoning behind adopting a 100-120ms cut-off is not specified within the aforementioned publications. Yet, this threshold has presumably arisen from the suggestion that stimuli cannot be identified when attended to for less than 100ms (Kowler, 2011; Land & Tatler, 2009; Salvucci & Goldberg, 2000). Conversely, evidence has affirmed that humans can correctly identify environmental characteristics of stimuli if these are present in the visual field for durations of as little as 17 to 50ms (De Wit et al., 2012). Particularly important are findings that humans can adapt kinematic limb trajectories in response to the appearance of an obstacle in the immediate travel path with a latency of 100-140ms (Brenner & Smeets, 2003; Weerdesteyn et al., 2004). Together, these findings highlight the important contribution of short dwell times, which would typically be excluded from fixation based approaches, in extracting visual information from the environment (see also: Cisek & Kalaska, 2010). Based on these works, a dwell based approach was applied throughout this thesis. Specifically, the percentage of the approach period participants point of gaze was within designated AOI was calculated (Hildebrandt & Cañal-Bruland, 2020; Miyasike-Dasilva et al., 2011; Parr et al., 2020) and compared to understand how gaze was allocated as participants overcame environmental demands.

The following five, mutually exclusive and exhaustive, areas of interest were classified on the basis of Ellmers et al., (2019) research: (i) *Walkway surface:* the area between the participant's starting position and the threshold of the belt surface; (ii) *Belt surface:* the surface of the conveyor belt, which started at the end of the walkway and ended with a transition onto a platform 3m from the walkway's threshold; (iii) *Penultimate step:* the location of the final step on the walkway before transitioning onto the belt surface. Using a custom MATLAB script, this location was derived on a trial-by-trial basis from the supporting foot's calcaneus marker position, taken as the contralateral foot crossed the threshold between the end of the walkway and start of the belt surface (e.g., establishing the foot was mid-flight), and footwear length; (iv) *Final step:* the location of the first step onto the belt surface. Using a custom MATLAB script, this location was derived on a trial-by-trial basis from calcaneus marker position, taken as the lead foot made contact with the conveyor belt surface, and footwear length; *(v) Other:* any gaze locations not captured by the above AOI's (Figure 3.5). AOI viewing data was normalised to the individual trial length by presenting data as the percentage of dwell time



between the start of the approach phase and foot contact with the belt surface (see: Ellmers et al., 2019).

Figure 3.5: Top view of approach walkway and belt surface showing the areas of interest considered for analysis (penultimate and final step, both black). The fifth AOI, ‘other’ accounts for the period of time gaze was not in these areas.

3.6 Successful locomotion in a moving surface paradigm

Stepping onto moving surfaces represents a task, which has been associated with public injury (Shiminke et al., 2013). Despite being recognised as a risk to public health (Beards et al., 2022), limited empirical research has measured human perceptual-motor behaviours in an escalator (or representative escalator) environment. As such, there is little information regarding the specific adaptive or maladaptive perceptual-motor behaviours that influence how pedestrians overcome the challenge of stepping onto a moving surface. Based on this gap in knowledge, I have measured a range of perceptual-motor behaviours commonly presented in adaptive locomotor literature (outlined in sections 3.4.3 and 3.5.1 above) in order to build up a portfolio of how an individual negotiates the challenge of stepping onto moving surfaces (e.g., Thomas et al., 2020). The current section will clarify the significance of adaptations across these variables in relation to the paradigm of stepping onto moving surfaces. In the following paragraphs specific measures related to successfully negotiating moving surfaces shall be outlined before progressing to detail adaptations associated with increased or reduced task demand.

Perturbation magnitude will be used as a measure of successful locomotion in the subsequent experimental chapters. The decision to utilise this variable was supported by research affirming that successful locomotion can be characterised as reducing prospective gait perturbations (Higuchi, 2013; Wu et al., 2017) and thus successful locomotion can be considered as having minimal deviation from a steady state (Bruijn et al., 2013). Furthermore, human factors based research exploring escalator incidents has identified hesitation (synonymous with a perturbation occurring during the approach to a moving surface) as associated with an increased likelihood of a fall (HSE, 2020; d2e, 2018). Accordingly, significant increases in perturbation magnitude identified between experimental conditions may denote maladaptive behaviour (e.g., a hesitation).

Incident reporting and observational analysis based research can provide insight into what contributes as ‘unsafe’ or maladaptive behaviours within the moving surface paradigm. Using a human factors based approach Beards and colleagues (2022) identified mis-stepping as a significant contributing factor to increased fall rate, noting that declines in perceptual-motor control associated with ageing may lead to a loss of foot placement accuracy or loss of balance, ultimately contributing to the increased fall frequency observed in older adult pedestrians (Beards et al., 2022). Accordingly, inaccuracy in the penultimate step location (e.g., increased variability in distance between toe placement and edge of the moving surface) may be considered a maladaptive behaviour when negotiating conditions with moving surfaces.

Online control has been associated with adaptations made to concurrent movement (Barton et al., 2019), which in the current context refers to adaptations made during the step onto the moving surface as well as ‘active’ regulation of foot positions, such as guiding the foot onto a targeted location mid-stride (Matthis et al., 2017). In the subsequent experimental chapters, adaptations associated with online control reflect changes made during the ‘final step’, which started when participants conpleted their last step on the walkway and terminated with participants making foot contact with the conveyor belt surface. As such, adaptations denoting online control include an increase variability in measures of Step length and Step time, as well as gaze behaviour adaptations such as reduced Look ahead distances, later Gaze transfer times away from Walkway and Belt footstep locations, and greater attention to proximal Areas of Interest. As regulating movement using online control has been recognised as being more cognitively and physically demanding than feed-forward control (Barton et al., 2019), such adaptations may suggest that environments or design interventions that invite these behaviours are associated with increased demand. Furthermore, falls have been suggested as occurring when the demands of an environment surpass an individual’s action capabilities (Chapman & Hollands, 2007), and therefore, the emergence of online control behaviours may be considered maladaptive.

Feed-forward control is associated with adaptations made prior to an obstacle or foot target (Barton et al., 2019) which in the current context refers to adaptations made as the participant approaches the moving surface. Adaptations associated with the use of feed-forward control include: reduced Toe distance variability; increased Approach time variability; increased Look ahead distances; earlier Gaze transfer times from the Walkway and Belt footstep locations; and greater attention to distal Areas of Interest. As regulating movement using feed-forward control has been associated with greater efficiency and reduced physical and cognitive demand, such adaptations may suggest that these behaviours, coupled with maintaining successful locomotion (e.g., no change in perturbation magnitude) reflects a reduced cost to physical resource and can be considered benificial.

CHAPTER 4: EVALUATING THE INTEGRATION OF EYE-TRACKING AND MOTION CAPTURE TECHNOLOGIES: QUANTIFYING THE ACCURACY AND PRECISION OF GAZE MEASURES

4.1 Abstract

The integration of mobile eye tracking and optoelectronic motion capture enables point of gaze to be expressed within the laboratory co-ordinate system, presenting a method not commonly applied during research examining dynamic behaviours, such as locomotion. This paper examines the quality of gaze data collected through the integrated eye tracking and motion capture system. Based on previous works suggesting that increased viewing distances are associated with reduced data quality, the accuracy and precision of gaze data associated with viewing floor-based targets is investigated. Participants (N=11) viewed floor-based targets at distances of 1-6m with a mean accuracy of 2.55±1.12°. Accuracy and precision measures (relative to floor targets) significantly (p<.05) reduced at greater viewing distances. Further, we considered if signal processing techniques may improve data quality and overcome data loss. Firstly, a 4th order Butterworth lowpass filter with cut-off frequencies determined via autocorrelation was evaluated. No significant main effect between conditions were identified, suggesting data quality was not significantly improved. Secondly, interpolation via Quintic spline was evaluated when treating gaps in the data of up to 1 second. Significant differences in mean absolute error were observed between 'original' and 'treated' datasets at gap sizes of 0.1 seconds or more, indicating this process was sufficient to overcome gaps of up to 0.1 seconds. It was concluded the integration of gaze and motion capture presents a viable methodology in the study of human behaviour and provide considerations for the collection, analysis, and treatment of gaze data that may help inform future methodological decisions.

4.2 Introduction

The past two decades have seen a notable increase in the development of research methods incorporating mobile eye tracking technologies to examine the visual control of behaviour across a variety of scientific domains (Tatler et al., 2011). By way of example, methods used in the study of social attention (Laidlaw et al., 2011) and expertise in sport (Vickers, 1996) have been enriched, leading to new proposals of dynamic visual control, which consider the function of eye movements relative to the coordination of the head and body (van der Kamp & Dicks, 2017). Within the field of perceptual-motor control, the accurate study of coordination between the eyes, head, and body has arguably been limited by the lack of suitable technology (Kothari et al., 2020). In such fields, researchers using head-worn eye trackers are predominantly interested in questions such as which objects in the world a person fixated, in what order, and for how long (Ellmers et al., 2020; Matthis et al., 2018; Niehorster, Hessels, et al., 2020). As such, eye movement data collected via head mounted eye tracking technology requires mapping onto locations in world space (Hessels et al., 2018). While mobile eye trackers deliver gaze data in a head-centered reference frame, simultaneous motion capture provides the means to express gaze data in a world-centered reference frame. Specifically, by combining eye position, derived from retroreflective markers attached to the mobile eye tracker, and eye orientation data, point of gaze can be expressed relative to the world-space coordinate system[6].

Although the integration of mobile eye tracking and motion capture systems to express point of gaze with a world-centred frame of reference is uncommon (however see: (Burger et al., 2018; Essig et al., 2012; Matthis et al., 2018), research capturing kinematic and gaze data has begun to progress our understanding of perceptual-motor behaviours (Domínguez-Zamora et al., 2018; Domínguez-Zamora & Marigold, 2021). In particular, Matthis, Yates, and Hayhoe

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[6] Please refer to: https://www.qualisys.com/webinars/tobii-pro-eye-tracking-and-motion-capture-integration

(2018) recently developed a method of integrating gaze and kinematic measures, expressing point of gaze within world-space whilst participants walked over terrains of differing complexity. Deriving eye and horizontal floor plane position from inertial measurement unit (IMU) sensors located on each participant's head and feet, and gaze orientation data from a mobile eye tracker, point of gaze was computed as the location where the gaze vector intercepted the floor plane[7]. Matthis and colleagues' method developed understanding of how people successfully overcome challenging environments, revealing that gaze and kinematic behaviours are adapted relative to the environment's specific demands. As such, their method signposted the potential benefits of integrating these distinct measurement systems in perceptual-motor control research domains requiring skilful coordination, such as locomotion (Higuchi, 2013b; Matthis et al., 2018) and sport performance (Dicks et al., 2010), as well as domains such as environmental representation (Tatler & Tatler, 2013) and object manipulation (Draschkow & Võ, 2016; van Dijk & Bongers, 2014).

Although data collected using motion capture and eye tracking systems have been integrated previously (Burger et al., 2018; Jantunen, Puupponen & Burger, 2020; Matthis et al., 2018) the quality of data, such as point of gaze accuracy and precision, in terms of world-space co-ordinates has yet to be evaluated. As such, this paper centralises around accuracy, defined as the difference between the recorded gaze position and the actual gaze position (Wang et al., 2017), and precision, defined as the ability to reliably reproduce a measurement given a fixating eye (Pastel et al., 2020) of data collected through the integration of mobile eye tracking and optoelectronic motion capture and then expressed in world-space co-ordinates.

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[7] For full detailed method see Matthis, Yates and Hayhoe (2018).

4.2.1 Evaluating optoelectronic systems for gaze data collection

When precise position or orientation-related analyses of human movements are required, optoelectronic systems represent the gold-standard in terms of accurately tracking (<1mm) anatomical positions (Spörri et al., 2016; van der Kruk & Reijne, 2018). Determining the position of the eye is essential to accurately expressing point of gaze in relation to the world co-ordinate system, therefore, utilising optoelectronic motion capture may enhance gaze data quality. Moreover, unlike IMU, optoelectronic systems allow features such as objects, obstacles, or foot targets to be digitised, and expressed within the world-space coordinate system (van der Kruk & Reijne, 2018; Matthis et al., 2018).

The ability to accurately translate point of gaze onto the environment may play a pivotal role in analysing gaze data. To date, as a person moves through the environment, determining point of gaze relative to environmental features has predominantly been achieved via analysis of scene camera footage (Hessels, Benjamins, et al., 2020; Jongerius et al., 2021; Kothari et al., 2020). In particular, a frame-by-frame approach has been commonly applied to consider the amount of time a person's point of gaze is located on designated environmental locations (Ellmers et al., 2016, 2020; Mele & Federici, 2012; Parr et al., 2020). However, it has been suggested that frame-by-frame analysis methods are prone to inter-observer error and have been considered time consuming (Duchowski, 2007; Hessels et al., 2020; Kiefer et al., 2017). Further, researchers evaluating eye-tracking data analysis have recently noted that eye-tracking research would benefit from more standardised analysis procedures to enhance comparison between studies and assessment of study quality (Jongerius et al., 2021). The capacity of optoelectronic data collection to express both point of gaze and the location of environmental features within a world-centred reference frame addresses these points by facilitating greater automation of the data analysis process, which promotes time efficiency, reduces inter-observer error, and greatly increases the number of trials that can be analysed. In turn, these attributes increase statistical power, which due to the time needed to manually code gaze data has been frequently recognised as low (Jongerius et al., 2021; Knudson, 2017). In addition to the advantages associated with automated data analysis, the ability to express both point of gaze and environmental features within the laboratory coordinate system allows researchers to evaluate the accuracy and precision of gaze data in terms of world-space.

4.2.2 Gaze data accuracy and precision

Aside from establishing the origin of the gaze vector (e.g., eye position), expressing point of gaze with a world-based frame of reference can be affected by the accuracy and precision of the eye tracking system (Ooms, 2015). Multiple factors influence gaze calibration and data quality, including task factors such as viewing distance and visual angle (Blignaut & Wium, 2014; Thibeault et al., 2019). Parallax error represents a common limitation associated with viewing distance and head-mounted eye-trackers, which occurs when the distance between the point of regard and the user (viewing distance) is different to when the system was calibrated. Because the scene camera and the eye are not co-axial, viewing distance and gaze angle effect the mapping between point of gaze and scene-camera footage (Mardanbegi & Hansen, 2012). However, by establishing the position of the eye via optoelectronic motion capture (e.g., mapping the eye position onto the world-space coordinate system rather than in relation to head-based camera footage), the spatial offset between eye and scene-camera should potentially alleviate parallax error. That said, although using motion capture to translate gaze data from head to world may lessen parallax error, issues may remain in data quality as a function of task factors, such as high speed movement though world space, or marker occlusion (Spörri et al., 2016).

MacInnes and colleagues (2018) considered the influence of viewing distance and angle by evaluating the quality of gaze data at distances of 1, 2 and 3 meters and lateral angles of -10, 0 and 10 degrees, reporting the mean accuracy of the Tobii Pro Glasses 2 system across the aforementioned conditions as 1.42 degrees of visual angle. Although accuracy may be expressed in terms of visual angle (e.g., 1.42 degrees), it is important to consider the effects the relationship between visual angle and viewing distance may have on accuracy when considering a world-based reference frame. For example, adaptive locomotor research indicates that visual information is exploited from distances within approximately 6m preceding a foot target or obstacle (Cornus, Laurent, & Laborie, 2009; Lee, Lishman, & Thomson, 1982; Montagne et al., 2000; van Andel et al., 2018). Assuming a constant accuracy value of 1.42 degrees, viewing an eye-height target located on a vertical plane (such as a wall) from a distance of 1m translates to a world-space accuracy of 2.5cm, whereas a viewing distance of 6m translates to an accuracy of 14.9cm. As such, an increase in viewing distance would lead to reduced world-space accuracy due to constant angles covering larger areas at larger distances.

During everyday locomotion people predominantly attend to task relevant ground-based locations in the lower visual field (Matthis et al., 2018; Marigold & Patla, 2008). When considering the world-space accuracy of ground based fixations, the angle of incidence must be considered alongside viewing distance. Assuming a constant eye height and constant accuracy (in visual angle), the distance along the horizontal plane increases non-linearly with viewing distance. For example, a fixed eye height of 1.57m (Adler, 1999) and an accuracy of 1.42 degrees is associated with a distance along the horizontal plane of approximately 5.5cm for a person fixating a floor based target, 1m ahead of their location. However, accuracy would decrease to 60.8cm when fixating a floor-based target that is located at a distance 6m away.

Although the combined influence of viewing distance and visual angle outlined above are simple to translate into world-space values using trigonometry, the accuracy of eye-tracking systems (in terms of visual angle) has also been shown to be influenced by a range of participant factors such as eye colour, contact lens use, and eye lash length (e.g., Blignaut & Wium, 2014; Thibeault, et al., 2019). Furthermore, MacInnes and colleagues (2018) also reported that accuracy decreased as viewing distance increased. Specifically, visual angles of 0.8, 1.6, and 1.8 degrees were reported for distances of 1, 2, and 3m, respectively. The fact that viewing distance and participant factors impacted eye tracking accuracy (MacInnes et al., 2018; Pastel et al., 2020) raises important considerations when measuring gaze behaviours throughout situations such as adaptive locomotion, where attending to distal information has been noted as vital (Higuchi, 2013). Additionally, MacInnes and colleagues reported reduced precision when visual angle increased, a result possibly associated with the location of the pupils relative to the eye-tracking system's cameras (Hornof & Halverson, 2002; Pastel et al., 2020). This is again an important consideration as a participant fixating a proximal ground-based location would exhibit greater visual angles compared to when fixating a target positioned at eye height, possibly reducing gaze data quality (MacInnes et al., 2018). Such findings indicate that world-space accuracy may not be wholly defined geometrically and establishes a need to consider the influence of viewing distances and visual angles on gaze data quality in terms of world-space co-ordinates when viewing floor-based locations.

4.2.3 Processing gaze data

Noise has commonly been acknowledged as a limitation with kinematic data (Camargo, Ramanathan, & Csomay-Shanklin, 2020; Winter, 2009) and is particularly prevalent with optoelectronic data collection methods. As optoelectronic motion capture provides the information required to translate point of gaze into the world-centred reference frame, data processing methods commonly employed to overcome noise may improve gaze data quality and accuracy. To reduce the influence of noise, and improve data quality, researchers have commonly applied a low pass Butterworth filter to data collected via optoelectronic motion capture (Parr et al., 2020; Spörri et al., 2016; van der Kruk & Reijne, 2018). Accordingly, filtering eye position data may improve data quality and accuracy when translating gaze position to a world-centred reference frame.

In eye-movement data, noise has also been identified as a property inherent to the measurement device (Niehorster et al., 2020). Similar to treating kinematic data, previous researchers have utilised a low pass Butterworth filter to treat gaze data during locomotor pointing tasks (Domínguez-Zamora, Gunn, & Marigold, 2018), or to smooth gaze data prior to event classification (Houpt et al., 2018). However, these approaches commonly apply standardised one-size fits all filter parameters to gaze datasets. Such an approach may not reflect the variable nature of gaze behaviours that are common both between and within participants (Dicks et al., 2017). In recognition of the individual nature of gaze data, an auto-correlation approach to determining the optimum low pass filter parameters (Challis, 1999) may be particularly beneficial and allow filter parameters to be objectively determined on a trial by trial basis (Davis & Challis, 2020).

Missing data has been acknowledged as a limitation of data collected through both optoelectronic motion capture (e.g., marker occlusion) and eye tracking (e.g., pupil identification loss; Blignaut & Wium, 2014; Duchowski, 2007; Hessels, Andersson, Hooge, Nystrom, & Kemner, 2015; Spörri et al., 2016). Across a range of disciplines, including eye tracking research, the use of splines has been commonly advocated as a simple yet robust method to interpolate missing data (Frank et al., 2009; Hessels et al., 2017; Howarth & Callaghan, 2010; Kamali et al., 2020). In particular, quintic, as apposed to cubic, splines have been recognised as capable of interpolating complex or variable movements (Grimshaw et al., 2019; Winter, 2009), qualities often noted within gaze data sets (Dicks et al., 2017). However, reduced accuracy has been identified as a limitation of treating larger gaps using splines (Howarth & Callaghan, 2010). To mediate this limitation, an upper gap size threshold of 100ms has been adopted when applying splines to interpolate gaze data (Frank et al., 2009; Hessels et al., 2017). However, as considered, a standardised one-size fits all gap size threshold parameter may not be best suited to treating variable gaze behaviours (Dicks et al., 2017). As such, the use of splines as a method of filling different sized gaps in gaze data, relative to world-space accuracy merits exploration.

While mobile eye trackers deliver gaze data in a head-centred reference frame for many research topics, such as adaptive locomotion, gaze data in a world-centred reference frame is considered beneficial (Matthis et al., 2018). One way to achieve this translation is to perform simultaneous motion capture of the participant's eye position, which provides the information required to perform the head to world transformation. Findings concerning eye-tracking data have alluded to task and participant factors that inhibit gaze data quality (Blignaut & Wium, 2014). Such findings establish a need to consider the influence of greater viewing distances and visual angles on gaze data quality in terms of world space co-ordinates. As such, this study primarily aimed to assess the accuracy and precision of eye tracking data collected using the integrated Tobii Pro Glasses 2 and Qualisys motion capture systems. Based on the importance of ground-based fixations throughout many activities of daily life, including locomotion, gaze data accuracy and precision shall be considered as participants attend to floor-based targets at distances between 1 – 6 metres. Building on previous work highlighting reductions in gaze data accuracy at greater distances, and greater visual angles (MacInnes et al., 2018), we hypothesise a reduction in accuracy when participants attended to the most proximal and distal floor targets (1 and 6m respectively). Issues such as noise and missing data have also been identified in both optoelectronic and eye tracking data sets (Camargo et al., 2020; Hessels et al., 2017). Subsequently, the second aim was to explore if signal processing techniques, such as filtering and interpolation, may help overcome such limitations and improve data quality when considering gaze data in terms of world space co-ordinates.

4.3 Methods

4.3.1 Participants

G*Power (Faul et al., 2007) was used to perform an *a priori* power analysis for a repeated-measures within factors ANOVA selected to detect differences in accuracy and precision measurements as a single group of participants attended to six ground based targets. The sample size required was calculated based on Cohen's guidelines (Cohen, 1988). The power analysis suggested that a sample size of eleven was required to detect a difference between the six ground-based target conditions with 80% probability. Following institutional ethical approval, eleven participants (*M* age = 29.36 ± 4.51; Male = 9) provided ethical consent and completed a single data collection. Consistent with previous research, a Snellen eye test established that no participant had deficits in visual acuity, with each participant scoring 20/40 vision or better (Young et al., 2012).

4.3.2 Hardware

A Tobii Pro Glasses 2 mobile eye tracker (Tobii, 2018) was used to measure gaze behaviour. The eye tracker consists of a lightweight (45g) fixed geometry frame containing four cameras, and 12 illuminators, which project near infrared light to create a pattern on the cornea and pupil of both eyes. The system allows the position of each eye to be recorded at 50Hz as per recommendations for research concerning larger gaze angles, such as the current study (Tobii, 2018). The glasses were connected to a portable recording unit which used image-processing algorithms and a physiological 3D model of the eye to estimate the position of the pupil relative to the glasses[8]. The recording unit allowed gaze data to be streamed real-time via Wi-Fi and interfaced with the Qualisys motion capture interface (QTM version, 2018.1).

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[8] Normally the point of gaze is overlaid onto footage captured through a forward-facing 'scene' camera mounted on the glasses frame, which allows for gaze location examination to be undertaken via frame-by-frame analysis or via a variety of behaviour identifying filters provided by the Tobii Pro Lab analysis software.

To track the origin of each eye’s gaze vector in the lab, a cluster marker (provided by Tobii) set comprised of six retroreflective markers was attached to the fixed geometry body of the eye tacking glasses (Figure 4.1). Within Qualisys track manager (QTM) software a 6 degrees of freedom (DOF) model was created from the cluster marker set allowing the location of each eye to be expressed relative to the lab coordinate system (QTM, version 2018.1).

Figure 4.1: Tobii Pro glasses 2 with motion capture markers attached.

4.3.3 Laboratory environment

A 14-camera system (Qualisys Oqus 300+) set to capture at 100Hz was used to record the position of the eye tracker cluster maker set. In order to account for variations in participant stature, cameras were typically positioned further back from the calibrated area and focused on the upper body. An area (approximately 6 x 1 x 2 m, x (anterior-posterior), y (medial-lateral), z (vertical) dimensions respectively) was calibrated with a mean marker deviation upper limit of 1.48mm being adopted based on average errors reported in multicamera photogrammetry literature (Summan et al., 2015).

4.3.4 Procedures and data collection

Participants were asked to tie back long hair and remove eye make-up before the eye tracker was fitted and secured in place using a head strap to reduce movement. The eye tracker was calibrated following Tobii's one-point calibration method. Following initial calibration, data were collected directly though the QTM interface with the gaze vector position visible in real-time (Figure 4.2). Following the steps outlined by MacInnes and colleagues (2018), viewing the real-time gaze vector position allowed researchers to judge calibration accuracy by asking participants to fixate on prominent eye-height features, such as the motion capture cameras. Large discrepancies in vector position, resulted in the glasses being refitted and the calibration process repeated until accuracy was considered acceptable.

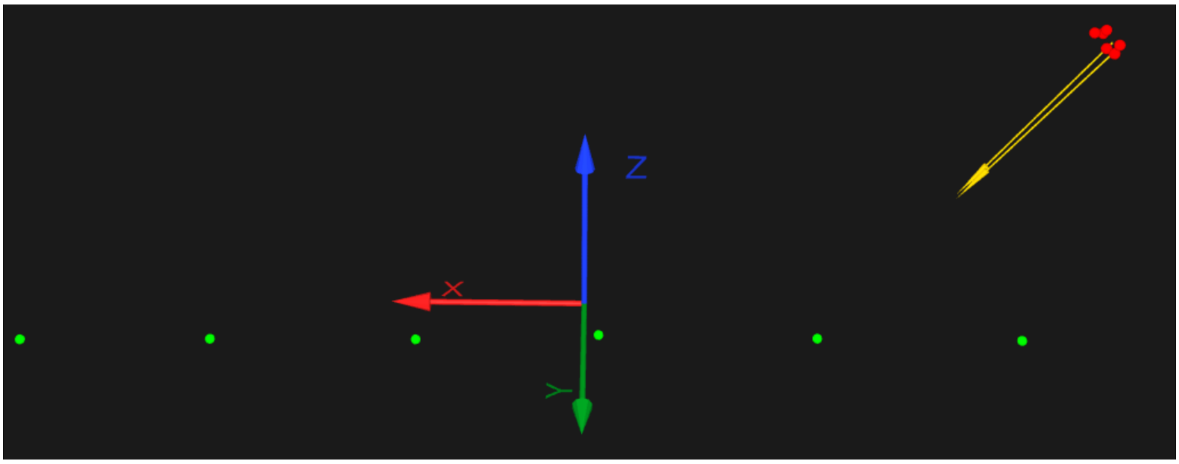

Figure 4.2: Gaze vector (Yellow), Retroreflective markers (red) and axis orientation visible in the QTM environment, (x, y, z axis denoted by red, green and blue arrows from the lab origin respectively). Green dots show the floor-based target positioned at 1m intervals along the x axis between 1m (floor target 1, extreme right) and 6m (floor target 6, extreme left) from the participant's position.

Following calibration, participants completed a single 30 second (1500 sample) data collection. From a fixed position, participants were instructed to sequentially fixate six ground based retroreflective markers (Target 1-6) positioned at 1m intervals along the x axis from the participant's standing position (Figure 2). Participants were instructed to fixate each target for approximately two seconds, moving from target to target sequentially for the whole 30 second (1500 sample) period.

Data from each eye was collected separately, and exported to MATLAB (MathWorks Inc, 2019) for processing, which allowed gaze accuracy and precision measures to be evaluated across 22 data sets (i.e., one data set per eye). The export consisted of a matrix of six rows and a column per sample of visual data collection. The first three rows represented the origin position within the lab coordinate system and the second three rows represented gaze orientation as the dimensions of a unit vector.

4.3.5 Calculating gaze location

Three distinct elements are required to be accurately measured to compute the gaze vector's intercept with the laboratory environment. These are the origin of the gaze vector, comprising of the coordinates of the gaze vector origin (e.g., eye position), gaze direction, and information about world layout, such as areas of interest, specified within the lab coordinate system. This section details the process for generating coordinates for the intercept of the gaze vectors with the floor, as specified as having a Z axis value (vertical height) of zero (Figure 2). Throughout this study the intercept along the x (anterior-posterior) axis was evaluated. This was due to the linear nature of locomotor pointing tasks, frequently examined throughout perceptual-motor control research (Ellmers et al., 2020; Hildebrandt & Cañal-Bruland, 2020; van Andel et al., 2018a) and the current study's aim to evaluate data quality relative to viewing distance[9].

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[9] This method can be expanded to allow computation of the y (medial-lateral) axis floor intercept, which enables a computation of a set of coordinates detailing the z axis intercept for non-linear tasks.

First, the angle of the gaze vector relative to the vertical plane was calculated (Figure 4.3, *a*). Because the gaze orientation was expressed in the dimensions of a unit vector (Figure 4.3, ĝ) knowledge of both the distance in the x direction (Figure 4.3, *x*) and the vector magnitude allowed the gaze angle (Figure 4.3, *a*) to be computed using trigonometry. Next, the look ahead distance (Figure 4.3, C) was calculated using the vertical eye position (Figure 4.3, A) and the gaze angle. Finally, the floor intercept relative to the lab coordinate system (Figure 4.3, D) was calculated through summing the eye's position in the x axis (Figure 4.3, B) and the look ahead distance (Figure 4.3, C). This procedure was repeated for each sample of capture using a custom MATLAB script.

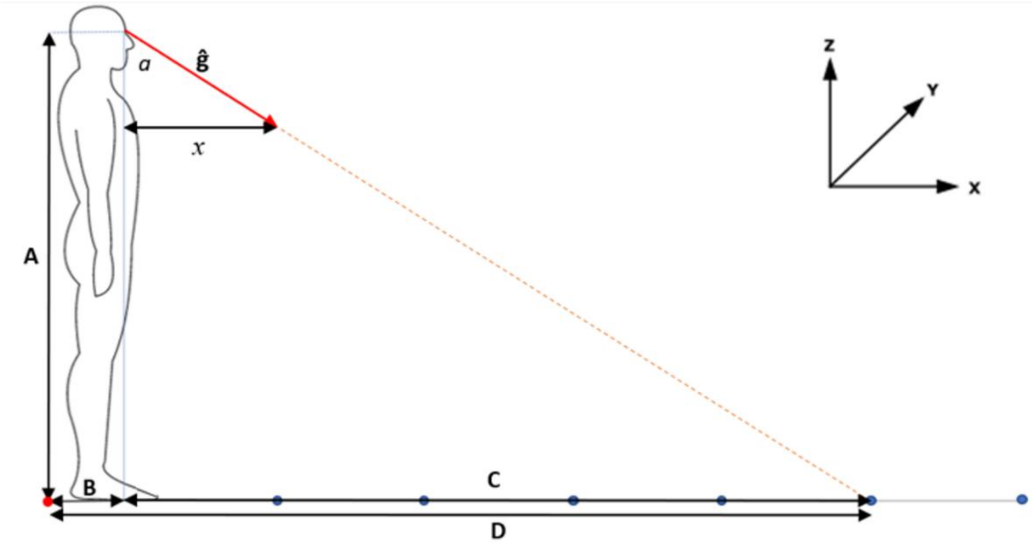

Figure 4.3: Computation of x axis floor intercept location. Red dot represents lab origin; Blue dots represent floor markers positioned along the ground plane (z=0); Red arrow represents gaze unit vector ĝ; orange dotted line extrapolated gaze vector included to clarify intercept location; *x* represents the gaze vectors x axis magnitude; Angle *a* represents the gaze angle from vertical plane; Length A represents eye z axis position; Length B represents eye z axis position; Length C represents look ahead distance; Length D represents x axis intercept distance.

4.3.6 Measures and Analyses

Using a custom MATLAB script, the gaze data that corresponded with the start and end of each floor target viewing period were manually identified from each participant's gaze data set, prior to data treatment. This approach allowed for the gaze transfer between targets (vertical lines, Figure 4.5) to be omitted from subsequent analysis. The identified samples (that correspond to each floor target viewing period) were then used to allow the gaze floor intercept location to be analysed relative to the target location.

To screen gaze data for inaccuracies and consistent with approaches applied to event classification filters (Duchowski et al., 2002), the visual angle of each eye, in relation to the z axis (Figure 4.3 *a*), was calculated in degrees from the imported unit vectors. Using MATLAB (MathWorks Inc, 2019), the angular velocity of each eye when attending to floor targets, was assessed against an angular velocity upper limit. This threshold was extrapolated from research establishing the velocity of vertical saccades is relational to angular magnitude (Collewijn et al., 1988). Specifically, based on the A-P displacement between floor targets at 1 and 2 (as associated with peak change in gaze angle) and participant eye height, a maximum amplitude between floor targets of 19.4 degrees was identified. Collewijn and colleagues suggested that the maximum speed of upwards and downward saccades (e.g., looking from floor targets 1 to 2, and back from targets 2 to 1) was consistent for amplitudes of up to 30 degrees and presented peak velocities of approximately 350 deg/s for saccades of 20 degrees. Data from one participant's left eye only exceeded this value (peak 373 deg/s) and thus was excluded from subsequent analysis.

Accuracy

The mean absolute error (MAE) was computed for each eye on a trial by trial basis. The distance between point of gaze and the floor target being fixated was computed for each sample, summed, then divided by the number of samples spent viewing the respective target (see: Dietzsch et al., 2017). MAE was computed for each eye and then averaged and used for statistical analysis (Chai & Draxler, 2014; Willmott & Matsuura, 2005). As accuracy is commonly expressed in eye tracking literature as the visual angle (in degrees) between the point of gaze and the target location (Holmqvist et al., 2010; MacInnes et al., 2018), the visual angle associated with each floor-based target's MAE was computed as follows:

$$Visual\ angle = tan^{-1}\left(\frac{Look\ ahead\ distance + (\frac{MAE}{2})}{Origin\ eye\ height}\right) - tan^{-1}\left(\frac{Look\ ahead\ distance - (\frac{MAE}{2})}{Origin\ eye\ height}\right)$$

The mean visual angle was computed from the data of both eyes to give a measure of accuracy associated with fixations on the floor-based targets and used to compare between distances.

Precision

In line with extant literature (Niehorster et al., 2020), precision of gaze position data was measured using the root mean square of the displacement between successive gaze position samples (RMS-S2S) and the standard deviation of the gaze position samples (STD). As such, both RMS-S2S and STD were calculated to measure precision for each of the identified fixation targets following the methods outlined in previous research (Niehorster, Zemblys, et al., 2020). These values were calculated for each eye on a trial-by-trial basis with a world based frame of reference[10].

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[10] For precision measures with a head-based reference frame see online supplementary material.

4.3.7 Signal processing

To consider the effect of signal processing on the resultant point of gaze, gaze origin and gaze angle data were filtered separately using a lowpass 4th order Butterworth filter, at the cut off frequency determined using autocorrelation (Challis, 1999). The autocorrelation function identified a range of frequencies between 5 and 10Hz (Mean = 7.2 Hz). To assess the influence of cut off frequency, eight conditions were tested with the point of gaze being computed using eye rotation data filtered at cut offs of 5, 6, 7, 8, 9, and 10 Hz (derived from the range of cut of frequencies identified, see Figure 4.4 for an example), the Autocorrelation frequency and the original untreated data. The accuracy MAE and precision RMSE-S2S measures were calculated between point of gaze and each of the floor targets (as above) for each of the data treatment conditions.

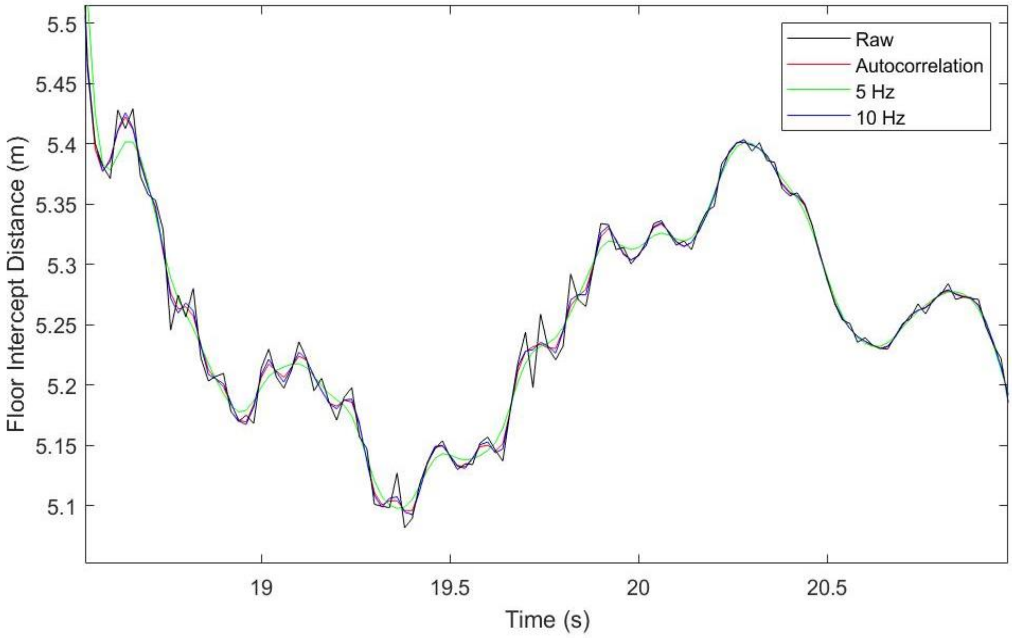

Figure 4.4: Visual representation of different filter parameters treating the same data as presented in Figure 4.5. Black line shows raw, untreated, data; Red line shows data filtered using the autocorrelation procedure; Green and Blue show data treated with filter parameters of 5 and 10hz respectively.

Gap filling

A method utilised by Musial, Verstraete and Gobron (2011) was adapted to ascertain the impact of the data treatment processes. Raw data were imported into MATLAB where two matrices (origin position and gaze orientation) were created for each eye. The location of missing data points in these matrices were indexed. The gaze orientation data were processed to compute gaze angle (eye rotation) using the procedure outlined in the methods section (Figure 4.3, angle *a*). The origin position and gaze angle data were processed using a quintic spline and the auto-correlation function outlined in the methods section. The processed data were then used to compute the gaze vectors intercept of the floor plane using the previously detailed method. Using the index of missing data, any artificial data points (e.g., were then removed and the floor intercept locations in the anterior-posterior direction for each eye were used to establish a baseline against which the effects of data treatment could be evaluated. That is to say, the original gaps were replaced to ensure artificial datapoints were omitted.

After establishing a baseline, akin to similar approaches taken in research evaluating the impact of data treatment on time series data (Musial et al., 2011), a second data set was created to represent missing data. To replicate missing data, a gap was created by removing values from the raw imported data. Using a custom MATLAB script, the position of the gap was designated using a random number generator function set to allocate a value ensuring a minimum threshold of 50 samples from the trial start and end points. The 50 sample cut off was selected to strengthen the comparison by avoiding a situation where the created gap overlapped the data's start and end points (Grimshaw et al., 2019). The position of the removed samples was recorded. To examine the effect of gap size on the treated data, eleven gap size conditions were created with the size of the gap created being manipulated in 5 sample intervals between 0 (filtered signal data with no gap) to 50 samples (akin to 0 to 1 second of missing data). Previous research (Musial et al., 2011) undertaking similar comparisons have advocated large data samples to further strengthen analysis. As such, 50 randomly positioned gaps were created (non-simultaneously) within each eye's data set. This approach allowed a total of 1100 comparisons (11 participants, 2 eyes, 50 gaps) to be made for each of the gap size conditions. Following the creation of gaps, and data treatment process data either side of the gap MAE was calculated between the original and gap filled data to allow the effect of data treatment to be evaluated (Musial et al., 2011).

4.3.8 Statistical analysis

For the MAE, RMS-S2S and STD measures, multilevel linear model repeated measures ANOVA's (alpha of 0.05) were undertaken using the nlme package in R (Pinheiro et al., 2020; RStudio Team, 2020). To explore the impact of target location, significant main effects were followed up using Tukey post hoc tests effect sizes (*r*) were calculated for these contrasts (Field, Miles & Field, 2012). When comparing gap conditions, multilevel linear model repeated measures ANOVA's (alpha of 0.05) was undertaken using the nlme package in R (Pinheiro et al., 2020; RStudio Team, 2020). Normality was assessed via box and Q-Q plots with spurious outliers treated via winsorizing to 90% (Field et al., 2012; Ghosh & Vogt, 2012). To explore the impact of gap size, significant main effects were followed up using Tukey post hoc tests, effect sizes (*r*) were calculated for these contrasts (Field, Miles & Field, 2012).

4.4 Results

The point of gaze floor intercept (Figure 4.5) indicated that all participants completed the task as requested. Visual inspection suggested that as look ahead distance increased, point of gaze accuracy decreased. Several instances of data loss (e.g., at approximately 2.5 seconds, Figure 4.5) for one, or both, eyes were identified. Across all trials mean missing data equated to 187.95 ± 160.05 samples (*M* = 12.53% *SD* = 10.67%).

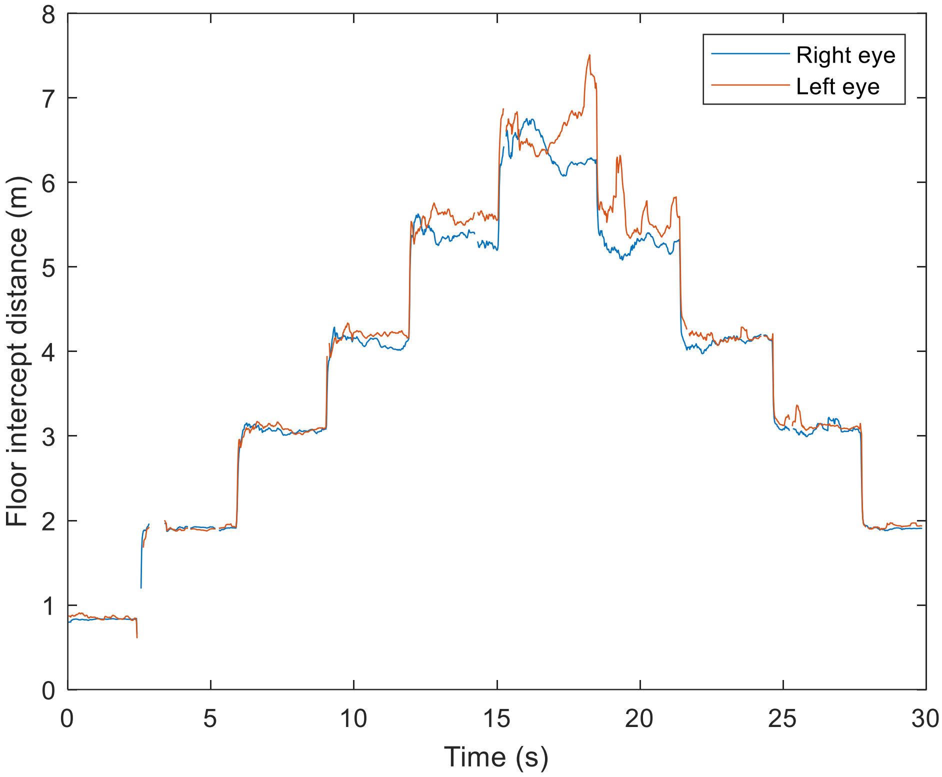

Figure 4.5: Untreated gaze data for the left and right eye (blue and red lines respectively) from one participant when looking at the six different floor targets.

4.4.1 Point of gaze accuracy

A multilevel repeated measures ANOVA indicated that floor target location had a significant effect on MAE, $\chi^2(5) = 97.84$, *p*<.001. Post hoc Tukey contrasts revealed significant increases in MAE (all *ps* <.05) between targets at 1m (*M*= 0.13m) and targets at 4, 5, and 6m (*M*= 0.33m, *r*=.71 ; 0.56m, *r*=.81; 0.82m, *r*=.85 respectively); target at 2m (*M*= 0.11m) and targets at 4m (*r*=.71), 5m (*r*=.81) and 6m (*r*=.86); target at 3m (*M*= 0.19m) and targets at 5m (*r*=.74) and 6m (*r*=.82); target at 4m and targets at 5m (*r*=.54) and 6m (*r*=.74) targets at 5m and 6m (*r*=.46); Figure 4.5).

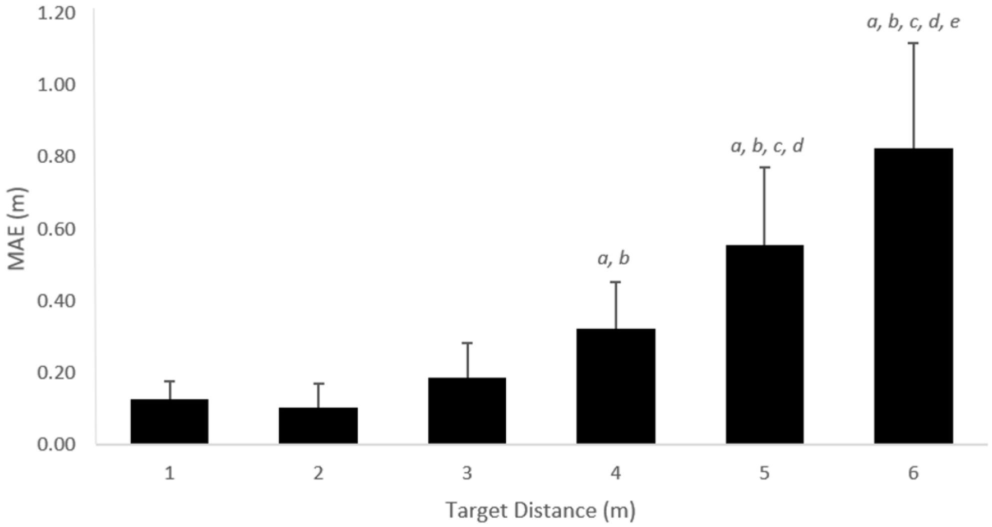

Figure 4.6: Accuracy at each floor-based target location. MAE is presented for each of the targets: *a* = significantly different (*p*<.05) to 1m target; *b* = significantly different to 2m target; *c* = significantly different to 3m target; *d* = significantly different to 4m target; *e* = significantly different to 5m target.

The visual angle in degrees associated with the MAE for each floor-based target was computed. The results (Figure 4.6) indicated a mean accuracy of 2.55 ± 1.12 degrees for all floor targets.

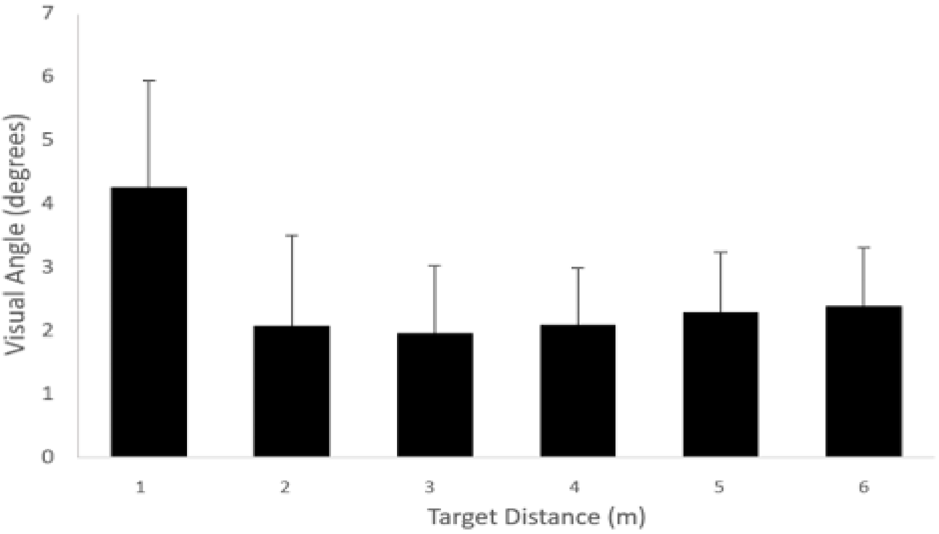

Figure 4.7: The visual angle associated with the MAE values for each floor-based target location. Targets at 2-6m were significantly different (*p*<.05) to 1m target.

A multilevel repeated measures ANOVA indicated that floor target location had a significant effect on degrees of visual angle associated with the MAE, $\chi^2(5) = 37.12$, $p < .001$. Post hoc Tukey contrasts revealed significant differences between target 1 and all other targets visual angle ($p<.05$, $r=.55$; .64; .65; .61; .59) for floor targets at 2m to 6m respectively) suggesting the most proximal target was associated with the largest inaccuracy (Figure 4.7). All other comparisons were non-significant ($p > .05$).

4.4.2 Point of gaze precision

A multilevel repeated measures ANOVA indicated that floor target location had a significant effect on the RMSE-S2S precision measure, $\chi^2(5) = 23.50$, $p < .001$. Post hoc Tukey contrasts revealed significant increases in RMSE-S2S ($p < .05$) between the target at 1m (M = 0.03m) and targets at 5m (M = 0.09m; $r=.57$), and 6m (M = 0.11m; $r=.54$); target at 2m (M = 0.03m) and targets at 5m; ($r=.53$) and 6m ($r=.51$); target at 3m (M = 0.05m) and target at 6m ($r=.45$; Figure 4.8). Moreover, a multilevel repeated measures ANOVA on the STD precision measure indicated that target distance had a significant effect, $\chi^2(5) = 51.14$, $p<.001$. Post hoc Tukey contrasts revealed significant increases in STD ($p < .05$) between target at 1m (M = 0.08m) and targets at 4m, 5m and 6m (M = 0.22m, $r=.64$; 0.28m, $r=.76$; 0.31m, $r=.73$ respectively); target at 2m (M = 0.07m) and targets at 4m ($r=.62$), 5m ($r=.74$), and 6m ($r=.72$); target at 3m (M = 0.15m) and targets at 5m ($r=.48$) and 6m ($r=.50$; Figure 4.9).

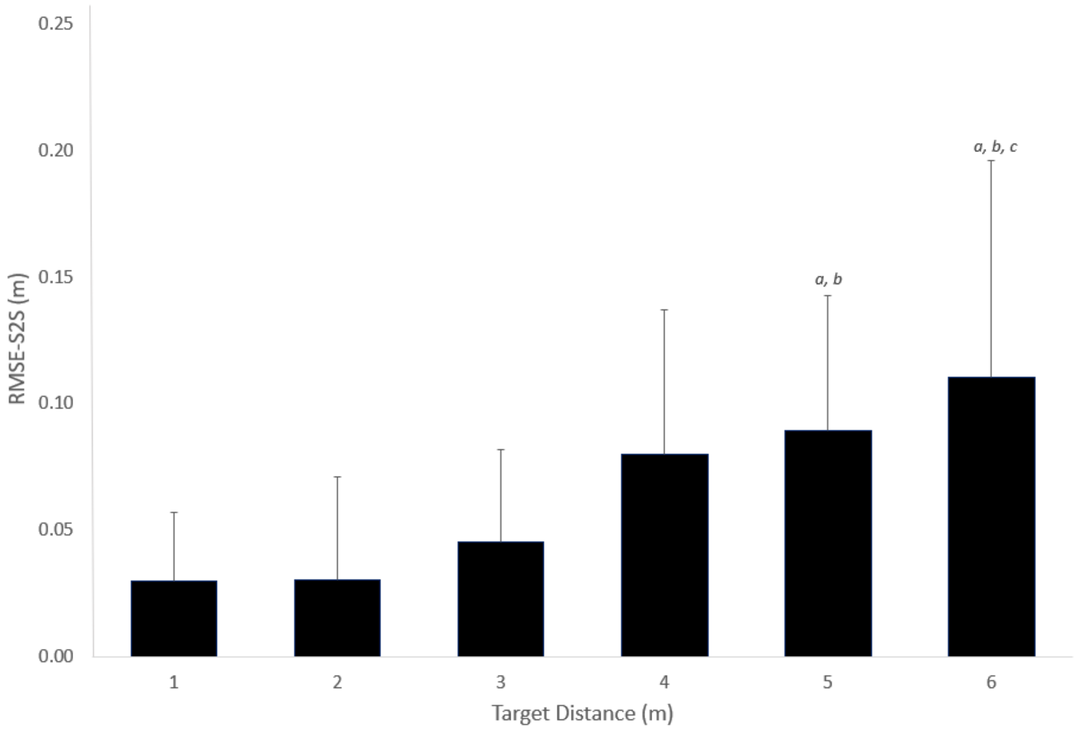

Figure 4.8: Precision at each floor-based target location. RMS-S2S is presented for each of the targets: *a* = significantly different (*p*<.05) to 1m target; *b* = significantly different to 2m target; *c* = significantly different to 3m target

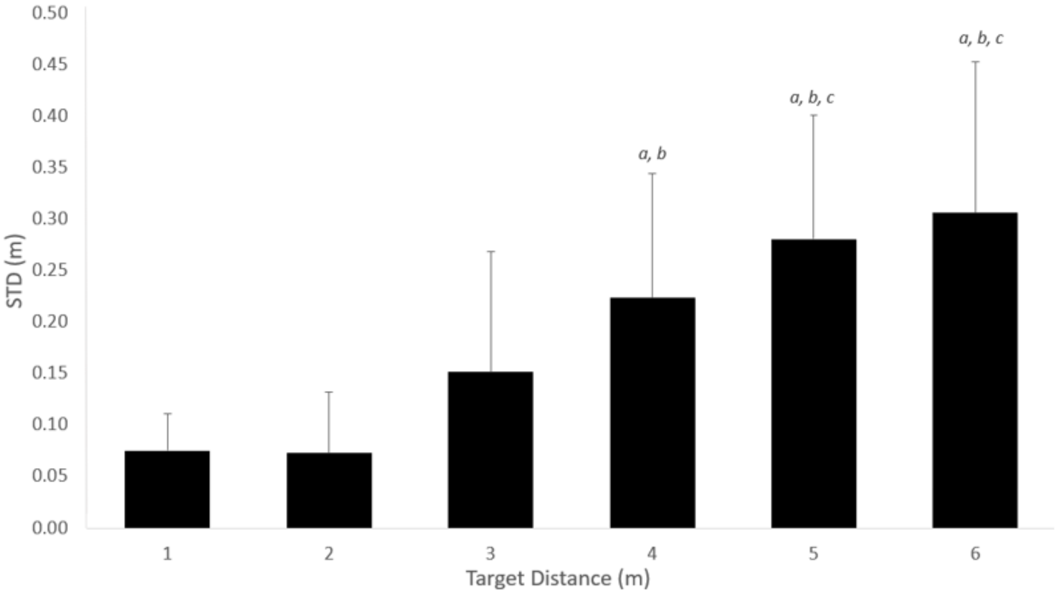

Figure 4.9: Precision at each floor-based target location. STD is presented for each of the targets: *a* = significantly different (*p*<.05) to 1m target; *b* = significantly different to 2m target; *c* = significantly different to 3m target.

4.4.3 Signal processing

Separate one-way ANOVA's (RStudio, 2020), identified no significant main effect for treatment condition for measures of MAE, $F(7,520) = 0.003$, $p = 1.000$, $\eta2 = 0.013$ or RMSE-S2S, $F(7,520) = 0.969$, $p = 0.453$, $\eta2 = 0.013$.

Table 4.1: Accuracy and precision of different data filter cut of frequencies.

	MAE (m)		RMSE-S2S (m)	
	Mean	SD	Mean	SD
Untreated data	0.356	0.038	0.064	0.060
Autocorrelation	0.363	0.037	0.052	0.042
5 Hz	0.359	0.037	0.047	0.037
6 Hz	0.360	0.037	0.050	0.040
7 Hz	0.360	0.037	0.053	0.044
8 Hz	0.360	0.037	0.056	0.046
9 Hz	0.361	0.037	0.058	0.049
10 Hz	0.362	0.037	0.061	0.051

4.4.4 Gap filling

The results comparing the MAE between treated data and data with created gaps (Figure 4.10) showed that gap size had a significant effect on MAE, $\chi^2(11) = 215.16$, $p<.001$. Post Hoc Tukey contrasts revealed no significant difference between processed data with no created gaps (0 second gap size) and unprocessed data ($p = .150$, $r =.15$). Significant differences (all *p*s <.05) were identified in MAE between treated data with gaps of 0 samples and data treating gap sizes of 0.1 seconds (10 samples) or greater (*r* = .74; .79; .78; .85; .87; .88; .92; .91; .88 for gap sizes of 0.1 to 1 second respectively).

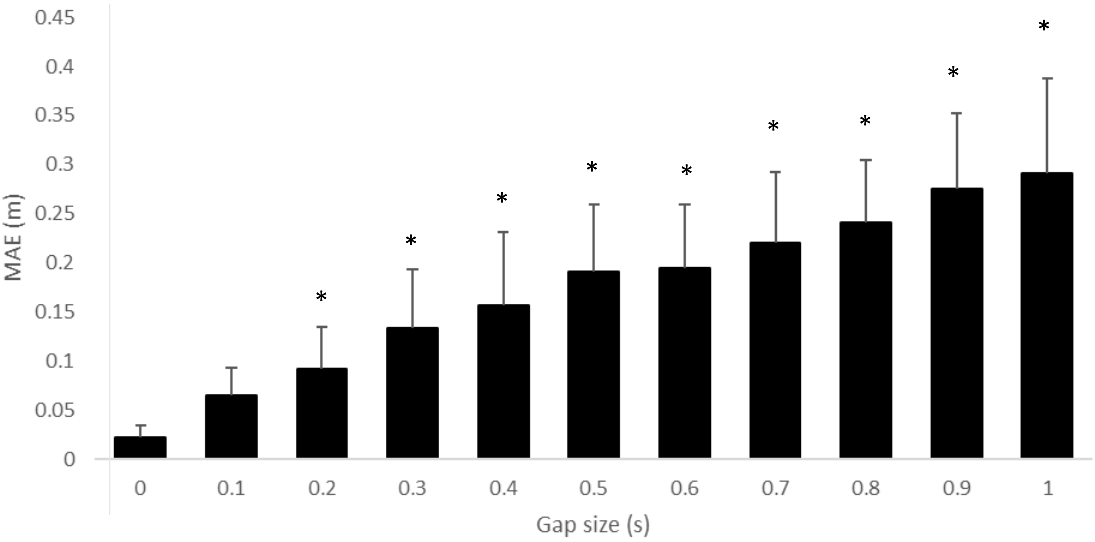

Figure 4.10. MAE associated with treating different gap sizes. 0 gap size represents comparison between processed and unprocessed data. * = significantly different (*p*<.05) to processed data with no gaps.

4.5 Discussion

Integrating mobile eye tracking and optoelectronic motion capture presents a method of translating gaze data to a world centred frame of reference (e.g., the laboratory co-ordinate system). Such an integration has provided an additional method of collecting and analysing human perceptual-motor behaviours. The primary aim was to assess the accuracy and precision of eye tracking data collected using the integrated Tobii Pro Glasses 2 and Qualisys motion capture system. Gaze data accuracy and precision were considered as participants were asked to attend to floor based targets at distances between 1m and 6m. Results indicated a reduction in accuracy and precision associated with increased look ahead distances. However, inconsistent with a geometric approach, reduced accuracy was acknowledged at the most proximal floor target. The second aim was to explore if signal processing techniques may help overcome limitations, such as data loss and decreased accuracy and precision in eye tracking data with increased viewing distance and angle. Results indicated that data treatment did not significantly alter data quality measures. Most notably, non-significant differences in accuracy measures when interpolating gaps of up to 0.1 seconds suggest that gap filling may present a solution to small gaps (e.g., less than 0.1 seconds) occurring within gaze data sets. This result is consistent with gap filling thresholds outlined applied in extant gaze research (Hessels et al., 2017). These findings and their implications shall be explored in more detail in the subsequent sections.

4.5.1 Accuracy and precision of gaze data

MAE results showed that point of gaze accuracy, in relation to world space, decreased at greater look ahead distances (Figure 4.6). Specifically, when looking at target 1 MAE was 0.13m whereas when looking at target 6 MAE was a significantly greater 0.82m. The reduced accuracy at greater viewing distances may be particularly important throughout perceptual-motor control research, such as studies of human locomotion (Ellmers et al., 2016; Hessels et al., 2020) and dynamic sport actions including goalkeeping in the penalty kick (Navia et al., 2017), where eye movements are characterised by fixations on floor-based locations. To further explore the effect of viewing distance on accuracy, the visual angle associated with each of the floor-based target locations MAE was computed (Figure 4.7). Our results suggested that accuracy, in degrees, at the most proximal target (4.27 degrees) was significantly less accurate than all other targets. This reduction in accuracy may be associated with the eye tracker's capability to accurately detect pupil location at larger gaze angles (Hornof & Halverson, 2002; Pastel et al., 2020) or because gaze is further from the glasses (central) calibration point (Niehorster, Santini, et al., 2020) as would be caused by floor based proximal locations. In support of this suggestion, comparing our findings to research examining eye movements oriented towards wall mounted targets, MacInnes and colleagues (2018) reported a mean accuracy of 1.42 ± 0.58 degrees for fixations on eye-height targets at distances up to three meters (0.8, 1.6 and 1.8 degrees for 1-3m, respectively). Comparatively, we reported a mean accuracy of 2.85 ± 1.24 degrees for floor-based targets up to the same distance (4.27, 2.24 and 2.02 degrees for 1-3m, respectively; Figure 4.7). The reduced accuracy presented in the current study affirms that the requirement to make proximal floor-based visual fixations appears to negatively influence accuracy. Considering the MAE and visual angle data together, the increased MAE at viewing distances of 4m and greater (Figure 4.6) and larger gaze angles associated with more proximal locations (Figure 4.7) aligns with our hypothesis suggesting that both larger visual angles (e.g., proximal locations) or large viewing distances (e.g., distal locations) may invite accuracy errors (MacInnes et al., 2018).

Results identified that precision measures (RMSE-S2S and STD) increased at greater look ahead distances (Figures 4.8 and 4.9). Specifically, precision measures at target one were 0.03m RMSE-S2S and 0.08m STD whereas target six measures were 0.11m RMSE-S2S and 0.31m STD. The reduced precession observed at greater viewing distances has potential consequences for future eye movement research. For example, automated gaze behaviour classification functions (e.g., fixation classification filters) are a common feature of eye tracking analysis packages. Within these packages, fixations are typically classified relative to a head based frame of reference as periods of stable eye movement (in degrees) (Hessels et al., 2018; Kothari et al., 2020). However, automatic gaze classification functions are limited when applied to free-moving tasks, such as ambulation, due to the capacity of participants to adjust eye position to counteract head movement (Hessels et al., 2018). Alternatively, adaptive locomotion literature has commonly classified fixations as periods of gaze stability in relation to areas of interest in the world (e.g., Ellmers et al., 2020). Integration of eye tracking with optoelectronic motion capture offers the capacity to express point of gaze within the environment thereby affording event classification during free-moving tasks. However, the increased variability (e.g., STD, Figure 4.9) identified when participants attended to distal (greater than 3m) floor-based targets may indicate a possible challenge to automating such an approach. Specifically, the geometry of the experimental set up used in the current study appeared to introduce a nonlinear increase in noise as a function of distance. Whilst utilising the gaze orientation signal for event classification may negate the issue of nonlinear noise with increasing distance (e.g., Hessels et al., 2017; Nyström & Holmqvist, 2010), it would not provide a possible solution to determining gaze events within dynamic everyday environments that require changes in look ahead distance to, for example, safely plan routes through cluttered environments (e.g., Matthis et al., 2018) or intercept a distal foot target (Hildebrandt & Cañal-Bruland, 2020).

Despite automated event classification becoming widespread throughout gaze behaviour research, the algorithms that facilitate behaviour classification are dependent on a head based frame of reference and are often contained within software packages that offer researchers limited flexibility over the analysis process (Niehorster, Hessels, et al., 2020; Vansteenkiste, Cardon, Philippaerts, & Lenoir, 2015). Previous work reviewing the treatment of gaze data has acknowledged that researchers should be mindful of the fact that results may be heavily dependent on the algorithms and parametrisations used (Kiefer, et al., 2017). Our findings reinforce this point and signpost that further work is required to investigate the ramifications of viewing distance on automatic gaze behaviour classification when head to world transformation of gaze data is required, particularly regarding dynamic tasks where floor based viewing distances exceed three metres.

The loss of data quality associated with increased viewing distances appears to be consistent for both the integrated data collection methods examined in the current study and scene camera data collection methods described in previous research (e.g., MacInnes et al., 2018). As such, selecting a viewing distance upper limit prior to the commencement of an experiment may offer a means of promoting data quality. Specifically, given that there were no differences between accuracy (MAE) in precision (STD) measures when participants fixated on targets between 1 and 3m away, a cut off distance of 3m may be considered appropriate for research measuring floor-based point of gaze. Alternatively, viewing distance based thresholds may be quantified relative to specific research questions. For example, research examining locomotor pointing in the context of a long jump task have considered areas of interest of 20 x 120cm (x and y dimensions) and approach distances of between 15.75 – 24.69m (Hildebrandt & Cañal-Bruland, 2020). At such distances, reduced accuracy may hinder the ability to accurately establish point of gaze within a relatively small area of interest. Given the variable (Dicks et al., 2017) and environment specific nature of gaze behaviours, and the variation in quality reported between participants (Blignaut & Wium, 2014; Thibeault, Jesteen, & Beitman, 2019), future research may wish to further consider gaze data quality to establish a viewing distance threshold that informs decisions regarding gaze data analysis relevant to individual study design. Although adopting a distal cut off for point of gaze data may help account for these limitations in future work, further research is clearly warranted.

4.5.2 Processing gaze data

Results from the current study highlight less precise data as occurring at larger viewing distances and gaze angles (see Figure 4.5 for an example). Instances of data loss were also noted (*M* = 12.53% *SD* = 10.67%). Previous research has separately identified several limitations associated with data collected using optoelectronic motion capture or eye tracking, with limitations including noise and missing data (Camargo et al., 2020; Hessels et al., 2017; Kurzhals et al., 2017; Spörri et al., 2016). Collecting data through the integrated system offers researchers scope to apply signal processing techniques (Grimshaw et al., 2019).

4.5.3 Filtering gaze data

Findings from the current study revealed that compared to the untreated point of gaze data, applying a 4th order Butterworth filter at the autocorrelation determined cut off frequency did not significantly change gaze data quality measures. Furthermore, no changes were identified when comparing untreated data to data filtered using a standardised cut off frequency. These findings also suggest that using the autocorrelation function to identify a cut off frequency does not significantly change data quality compared to filtering using a single cut off frequency. However, perceptual-motor control literature has frequently acknowledged that gaze behaviours are influenced by a myriad of factors including the performance environment (Matthis et al., 2018), the task being performed (Huys & Beek, 2010), and the participant's abilities (Ellmers et al., 2020). Accordingly, the use of the autocorrelation function may present a flexible method of treating gaze data that respects the diversity of perceptual-motor behaviours not captured within the data set of the current study. For instance, further research is required to establish the effect of these data treatment processes on gaze data collected in settings such as fast-paced movement or target interception (e.g., Navia et al., 2017).

4.5.4 Gap filling gaze data

Previous literature pertaining to data collected via both optoelectronic capture and eye tracking have highlighted instances of missing data (Duchowski, 2007; Hessels, Andersson, & Kemner, 2015; Spörri et al., 2016). Our findings were consistent, noting that missing data was commonly overserved. To overcome this limitation, a quintic spline was applied to the data set. Because reduced accuracy has been identified as a limitation of treating larger gaps using splines (Howarth & Callaghan, 2010) our aim was to compare treated and original data when filling gaps of different sizes (Musial et al., 2011).

When not filling gaps, no significant difference was identified between treated and the original gaze intercept data. The absence of differences indicates that the treatment process did not significantly change point of gaze location when there were no gaps in the data. Further, the lack of significant difference up to a gap size of 0.1 seconds (Figure 4.10) suggests that the data treatment process was sufficient to overcome missing data spanning less than 0.1 seconds.

However, significant differences were observed at gap sizes of 0.2 seconds or more, which is consistent with previous research suggesting increased error when treating larger gaps (Howarth & Callaghan, 2010) and gap sizes thresholds (0.1s) outlined previously in gaze methodology research (Hessels et al., 2017). To account for this, establishing a maximum gap size threshold based on the largest non-significant gap size may present one method of limiting the accuracy reduction associated with treating gaze data. For example, our findings suggest that the data treatment method was sufficient to overcome gaps in the data up to an upper gap size threshold of 0.1 seconds. Although this upper gap size threshold may offer a guide for future research, caution is recommended in universally applying this threshold. Accordingly, future research may undertake a similar analysis in order consider the implications associated with treating data collected across a wider array of research methods. Alternatively, considering MAE associated with each gap size may present a method of establishing an upper gap size threshold. For example, the MAE associated with filling gaps of 30 samples (0.19m) is similar to the MAE associated with look ahead distances of 3m (0.19m). As such, it may be appropriate for researchers to establish a threshold based on the size, or location, of areas of interest being evaluated, with larger areas being less sensitive to the accuracy loss incurred by filling larger gaps.

Although similar procedures are offered through commercial software packages (e.g. Tobii pro lab), the algorithms in such software have been considered inflexible, with results being influenced by a process that researchers have limited scope to control (Niehorster, Hessels, et al., 2020). Moreover, such packages often focus on identifying gaze behaviours rather than promoting measurement accuracy (Hessels et al., 2017; Kiefer et al., 2017). Considering that these processes influence the reproducibility of eye tracking research, investigators have recommended, and developed, ‘open source’ eye tracking analysis packages (Niehorster et al., 2020). Akin to these approaches, exporting the eye position (motion capture) and orientation (eye tracker) data directly into processing software (e.g., MATLAB) vastly increases the range of treatment options available. Furthermore, greater focus on the development of algorithms for the categorisation of gaze events, such as fixations, pursuits, and saccades, while the head is free (Kothari et al., 2020; Niehorster, Hessels, et al., 2020) could be beneficial to the wider research community. Future research may wish to consider if spatiotemporal analysis of world-space gaze location may offer a parsimonious approach to categorising gaze events. Overall, this represents a major advantage to gaze behaviour research and signifies that the integration may offer a platform that encourages greater clarity and innovation regarding the capture and analysis of gaze data.

4.6 Conclusion

The primary aim of this study was to assess the accuracy and precision of eye tracking data collected using the integrated Tobii Pro Glasses 2 and Qualisys motion capture system. Gaze data accuracy and precision were evaluated as participants attend to floor-based targets between distances of 1 – 6m. Supporting our primary hypothesis, which proposed reduced accuracy when participants attend the most proximal and distal floor targets, we found that both accuracy and precision were reduced at viewing distances of greater than 3m. Further, we found evidence suggesting that greater gaze angles, such as those caused by attending to ground based locations at approximately 1m, also reduced accuracy. These findings highlight a need for future research to review the quality of gaze data collected at distances greater than 3m across a wide range of contexts and indicates researchers should consider the implications of data quality throughout experimental design. With this in mind, future research may wish to collect gaze data with and without motion capture integration to compare the quality of data collected through both methods.

The second aim was to explore if decreased accuracy and precision of gaze data with increased viewing distance and angle, as well as loss of gaze data could be addressed via signal processing methods. We found that filtering the data using a low pass Butterworth filter at a variety of cut-off frequencies identified using an autocorrelation function did not significantly change data quality, however, gap-filling using a quintic spline was sufficient to overcome missing data spanning less than 0.1 seconds. Future research should build on these findings and consider if procedures outside of the scope of this paper, such as adaptive filtering, offer solutions to these issues. Finally, with the integration of gaze and motion capture becoming a viable methodology in the study of human behaviour, we have provided several primary considerations for the collection and analysis of gaze data that may help inform future methodological decisions.

CHAPTER 5: THE VISUAL CONTROL OF LOCOMOTION WHEN STEPPING ONTO MOVING SURFACES: A COMPARISON OF YOUNGER AND OLDER ADULTS

5.1 Abstract

Perceptual-motor research has primarily examined behaviours associated with constrained accuracy such as locomotor pointing, obstacle avoidance, or rough terrain walking. Despite the myriad of challenges encountered during daily locomotion, alternative challenges to successful locomotion, such as moving surfaces, have received comparatively little attention. Subsequently, in the current study, the locomotor control of younger and older adults were investigated when stepping onto moving and non-moving surfaces across four conditions of increasing difficulty: (i) stepping onto static surfaces without demarcation lines; (ii) static surfaces with demarcation lines; (iii) moving surfaces without demarcation lines; and (iv) moving surfaces with demarcation lines. Twelve younger adults (18-40 years, Male = 8) and 15 older adults (60-81 years, Male = 5) walked along an approach walkway and stepped onto a conveyor belt surface. Perceptual-motor behaviours were recorded using a combination of optoelectronic motion capture and mobile eye tracking equipment.

A two (age group) x two (surface condition) x two (demarcation conditions) linear mixed model indicated all participants maintained successful locomotion across all conditions as indicated by a non-significant difference in perturbation magnitude ($p > .05$). However, significant between-subject effects were identified with older adults transferring gaze from the final step on the approach walkway location (between 464ms in the static without demarcation lines condition and 266ms in the moving without demarcation lines condition) earlier than younger adults in all experimental conditions, which has been associated with increased fall risk. Overall, the current study suggests that adaptive behaviours emerge relative to the environment's specific demands and the individual's action capabilities.

5.2 Introduction

When walking over flat, obstacle free terrain, human behaviour primarily unfolds as a function of the human body's physical dynamics (Selinger et al., 2015). In flat terrain, gait cycle mechanics represent an inverted pendulum, maximising the exchange between potential and kinetic energy (Kuo, 2007), with relatively minimal demands placed on the visual system to guide movement (Matthis & Fajen, 2014). However, when negotiating challenging environments such as rough terrain, successful locomotion is defined by the ability to adapt to the increased demand on balance, which is primarily achieved by adapting locomotor and gaze behaviours to reducing gait perturbations (Higuchi, 2013; Wu, Brown, & Gordon, 2017). Urban environments in particular receive high footfall and contain numerous challenges, with examples including: negotiating closing apertures (Cinelli & Patla, 2008); avoiding other pedestrians (Dicks et al., 2016), and stepping onto moving surfaces, such as travellators and escalators (Hsu et al., 2015).

In experimental laboratory settings, researchers have manipulated environmental challenges by limiting foot holds, adding obstacles, or including foot-targets, all of which require accurate movements (for reviews, see Barton, Matthis, & Fajen, 2017; Higuchi, 2013). Studies have reported consistent gait adaptations that are proportionate to increasing accuracy demands (Domínguez-zamora et al., 2020; Marigold & Patla, 2007, 2008; Matthis & Fajen, 2014; Patla & Greig, 2006), such as increased approach times, reduced stride lengths, and slower step speeds (Swart et al., 2020). Whilst current understanding has been enriched through the extant research described, it has been suggested that understanding of perceptual-motor control using paradigms that characterise very specific aspects of human behaviour such as accurate stepping may not represent how people overcome the diverse locomotor challenges encountered throughout daily activity (Lappi & Mole, 2018; van Andel, Cole, & Pepping, 2018). Therefore, in order to address such a suggestion, the current study will set out to study the commonly experienced locomotor challenge of stepping onto a moving surface, which is encountered when using escalators and travellators. Indeed, despite fall-related escalator injuries being commonplace (Beards et al., 2022), there have been minimal research attempts to study locomotion in this setting (Hsu et al., 2015).

5.2.1 Affordance-based control

One account of visually guided action that has begun to receive increased consideration in the literature is Fajen's (2005) affordance-based control. Affordance-based control proposes that the visual control of action is predicated on an individual’s sensitivity to their own action capabilities (Fajen, 2007; Harrison et al., 2016). For example, Fajen (2005) measured deceleration rates when participants were required to break in order to avoid a collision during a simulated motor driving task. Multiple patterns of successful behaviour were demonstrated with participants adhering to the boundaries of their action capabilities, ensuring that the necessary deceleration required to stop did not exceed the maximum possible deceleration (Fajen, 2005). Such findings imply that the control of movement may adhere to a ‘safe-region’, in which individuals are acting both within their action capabilities and at a sufficient rate to successfully overcome environmental demands, suggesting that there are multiple trajectories that correspond with accurate behaviour.

The emphasis that affordance-based control places on action capabilities co-determining visual control has potentially important implications for understanding how ageing influences locomotor behaviours (Scuffham & Chaplin, 2003; Uiga et al., 2015). Specifically, studies comparing younger and older adults commonly report reduced action capabilities with advancing age. For instance, factors which have been linked to reduced gait stability and increased fall risk in older adults have been associated with loss of strength through reduced muscle mass (Arnold & Bautmans, 2014), as well as inhibited range of motion (Kovacs, 2005; Liu, Chan, & Yan, 2014; Maidan et al., 2018; Weerdesteyn et al., 2005). Accordingly, younger and older adults have often been compared when negotiating various environmental challenges (Chapman & Hollands, 2007; Muir et al., 2015; van Andel, Cole, & Pepping, 2018). Findings have revealed changes in older adult kinematics including reduced step length and gait speed, which are proposed to be indicative of a 'cautious gait', which are thought to proactively mitigate against perturbations (Kal & Ellmers, 2020; Lawrence et al., 2015; Marigold & Patla, 2008; Reelick et al., 2009; Swart, Otter, & Lamoth, 2020; Thomas et al., 2020). Moreover, equivalent gait adaptations such as reduced step length have been reported for younger adults when negotiating more challenging terrains (Matthis, et al., 2018). Such findings can be interpreted in line with Fajen's (2007) affordance-based control, where such locomotor adaptions appear to be functional and ensure that the demands of successful locomotion do not surpass an individual's action capabilities (e.g., as a function of age) or terrain complexities (e.g., environmental challenge).

5.2.2 Gaze behaviours during locomotion

Unlike the kinematic adaptations described, the factors affecting visually guided movement during daily locomotion are arguably less well understood (Harrison et al., 2016; Domínguez-Zamora & Marigold, 2019; van Andel et al., 2018). During locomotor tasks that require accuracy in stepping actions, participants have been found to attend to (fixate) proximal foot target locations for longer durations prior to foot placement and preview more distal foot targets for a shorter duration, consequently reducing the overall look-ahead distance that gaze is oriented along the travel path (Domínguez-Zamora & Marigold, 2019; Ellmers, Cocks, & Young, 2020; Ellmers & Young, 2019; Matthis et al., 2018). These findings have been interpreted as evidence of *online* control, which proposes that locomotion is underpinned by the regulation of concurrent movements (Fajen & Warren, 2007; Matthis, Barton, & Fajen, 2017; Zhao & Warren, 2015, 2017). In contrast, studies that have reported an increase in look ahead distances and earlier gaze transfer times from proximal locations prior to foot placement, have been interpreted as evidence of *feed-forward* control, which suggests that visual information is exploited over several steps rather than a step-by-step basis (Matthis & Fajen, 2014).

Online and feed-forward modes of control have been reconciled in the work of Matthis et al (2017), who proposed that feed-forward control may be adopted to alter the ballistic trajectory of the centre of mass (COM), synergistically enhancing prospective step accuracy and therefore reducing the demands placed on online control. However, although people are capable of exploiting the benefits of online and feed-forward control (Barton et al., 2017), research comparing young and old adults gaze behaviours has reported that older adults appear to prioritise feed-forward control (Chapman & Hollands, 2007; Domínguez-zamora et al., 2020; Ellmers, et al., 2020; Muir et al., 2015; Young & Hollands, 2010). Specifically, it has been suggested that online control is more physically and cognitively demanding than feed-forward control (Ellmers et al., 2020; Ellmers & Young, 2019; Holtzer et al., 2015; Wagshul et al., 2019). The emergence of feed-forward adaptations may reflect the sensitivity of older adults to their action capabilities, with such calibration (Ellmers et al., 2018) enabling older adults to maintain successful locomotion without surpassing the ‘safe-region’ of their action boundaries (Fajen 2007).

5.2.3 The current study

Escalator-related injuries commonly result in medical treatment and older adults over the age of 60 in particular appear to reflect a large number of reported incidents (Beards et al., 2022; Schminke et al., 2013). However, despite this there have been no attempts to study the difference between younger and older adults when stepping onto moving surfaces. In order to address this gap in the literature, a novel experimental paradigm was used to examine younger and older adults when stepping onto moving and non-moving surfaces, with and without accuracy requirements. Specifically, the study examined four conditions of increasing difficulty: (i) locomotor control when stepping onto static surfaces without demarcation lines; (ii) static surfaces with demarcation lines; (iii) moving surfaces without demarcation lines; and (iv) moving surfaces with demarcation lines.

It was hypothesised that younger adults would use both online and feed-forward modes of control, whereas older adults would be more reliant on feed-forward control to overcome increasing task difficulty. If feed-forward control is more prevalent in older adults when overcoming conditions of increasing difficulty, it was expected that the following changes would be observed during the approach to the moving surface: significantly reduced toe distance variability in the step preceding the transition onto the belt surface, as participants manipulate subsequent COM trajectory (Matthis et al., 2017); earlier gaze transfer relative to the final foot placement on the walk-way (Chapman & Hollands, 2007; Domínguez-zamora et al., 2020); reduced attention to proximal locations during the approach (Chapman & Hollands, 2006, 2007; Young & Hollands, 2012) and increased gait perturbation (symptomatic of less successful locomotion; Higuchi 2013). Secondly, it was hypothesized that gait and gaze adaptations shall be relative to increased environmental demand. As ‘cautious gait’ adaptations have been suggested to mitigate perturbations when overcoming environmental challenges, it was expected that significantly increased approach times and decreased step length would be observed as participants step onto the belt surface as participants (irrespective of age) negotiate more demanding conditions (Swart et al., 2020; Thomas et al., 2020; Thompson & Franz, 2017).

5.3 Methods

5.3.1 Participants

Research investigating adaptive locomotor behaviours (Chien et al., 2018; Ellmers, Cocks, Doumas, Williams, & Young, 2016; Matthis & Fajen, 2012, 2014; Matthis, Barton, & Fajen, 2015; Muroi & Higuchi, 2017) have reported large effect sizes (partial eta squared >0.14; Cohen, 1988) between 0.52 and 0.88 for kinematic variables (e.g., approach time and step length). Based on these values, an a priori power analysis was conducted for between factors using G*Power (Faul et al., 2007). The power analysis determined that a minimum of 12 participants per group would be required to obtain 80% power (Cohen, 1988).

Twenty-seven participants were grouped based on age boundaries used in previous research (Alcock et al., 2013; McCrum et al., 2017; Schminke et al., 2013). Younger adults (18 – 40 years, M = 26.5 SD = 5.7 years, *n* = 12, Male = 8) and older adults (60 years and older, M = 71.5 SD = 6.9 years SD = 5.7 years *n* =15, Male = 5) were recruited from the university and local community. A questionnaire battery was administered to examine self-reported differences between the two groups (Malhotra et al.., 2015; Uiga et al., 2018; Young., 2016; Young et al., 2012). The Falls Efficacy Scale international (FESi) was selected to provide a measure or fear of falling (Yardley et al., 2005). The Activities Balance Confidence scale (ABCs), was also undertaken as this has been noted as more suitable to detect the loss of balance confidence in higher functioning older adults (Powell & Myers, 1995); and the Reinvestment scale (Masters et al., 2005) questionnaires were completed prior to data collection. Ethical approval was granted at an institutional level (Appendix 1) with all participants providing signed consent, establishing no history of falling or physiological and neurological impairment.

5.3.2 Apparatus

Fourteen optoelectronic cameras (Oqus 300/310, Qualisys Sweden), sampling at 100Hz encircled the conveyor belt area (5x1x2m, x,y,z dimensions respectively), which was dynamically calibrated with a marker deviation upper limit of 1.48mm applied to promote accuracy (Summan et al., 2015). Participants were instrumented with spherical retro-reflective markers (12mm diameter). Collectively these markers enabled body segments to be modelled following C-Motion (2018a) guidelines. The markers were placed bilaterally on: anterior superior iliac spine, posterior superior iliac spine; femur greater trochanter, femur medial condyle, femur lateral condyle; tibia medial malleolus, tibia lateral malleolus, base of 2nd metatarsal, base of 5th metatarsal and calcaneal tuberosity. A further four cluster markers were attached to the lower limbs with elasticated straps located on the thigh midway between the greater trochanter and lateral condyle of the femur and on the shank midway between the lateral condyle of the femur and the lateral malleolus. The dimensions of each participants footwear were also recorded to ascertain the distance between the end of footwear and the start of the moving surface (i.e., conveyor belt). A Tobii Pro Glasses 2 mobile eye tracker (Tobii, 2018) was integrated and synchronized with the optoelectronic motion capture system (Qualisys, 2018). Following a one-point calibration of the eye-tracker, which followed Tobii (2018) guidelines, in order to promote accuracy, a post-calibration process based on previous eye tracking methodologies (MacInnes et al., 2018; Thibeault et al., 2019) was completed in which participants were required to fixate various locations allowing visual judgement of gaze vector accuracy.

5.3.3 Procedure

From the start location, participants walked along a two-metre walkway at their own pace, stepped onto a conveyor belt and stood stationary on the belt surface until the end of the trial (total trial duration of 8 seconds). The height of the approach was flush with the belt surface, alleviating any potential gait inconsistencies induced through changing surface height. An approach distance of two meters was selected based on distances found between start positions and targets or consecutive targets in previous locomotor pointing research (Chapman & Hollands, 2006b; Uiga et al., 2018). This approach distance recognises that when transitioning onto moving surfaces unconstrained long approach distances are often infeasible. For example, when using an escalator, people are commonly required to first negotiate another person or a barrier, meaning that a typical approach distance will equate to 2m (d2e, 2018). To promote a natural gait pattern, the leading foot used to step onto the belt was not regulated. Consistent with the most common escalator characteristics in the UK, the width of the conveyor belt was 1m, and in the moving condition, the belt was set to move at a constant speed of 0.50m.s^{-1} (CIBSE, 2015; Figure 5.1).

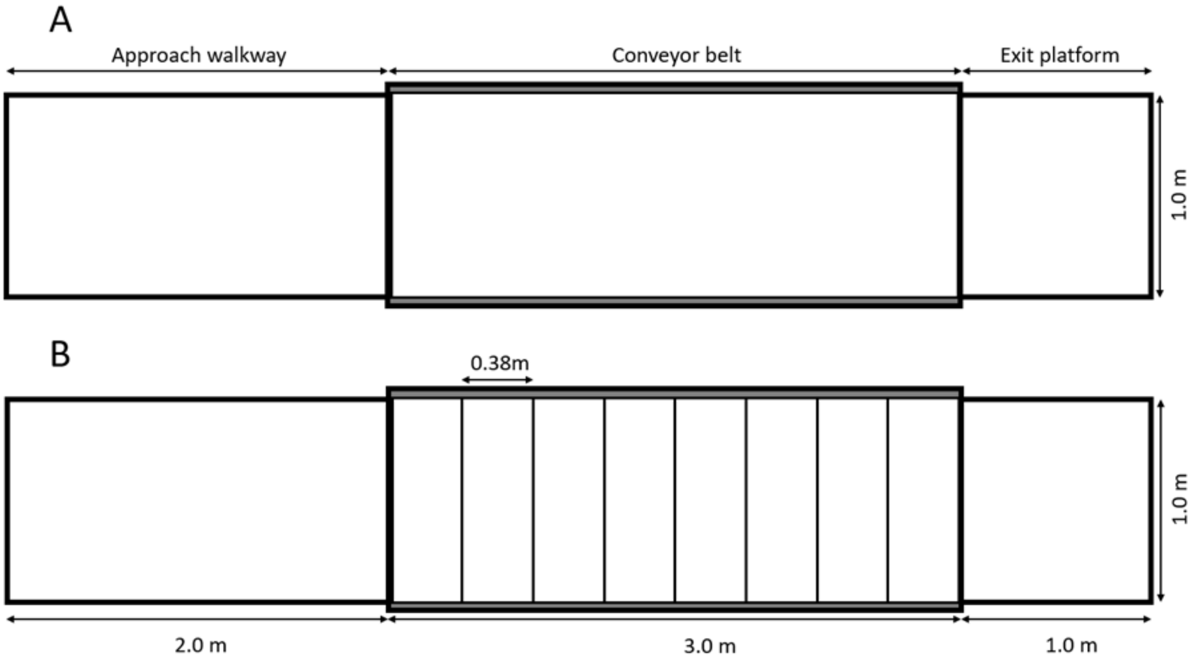

Figure 5.1: Top view experimental conditions showing A: dimensions of the approach walkway, conveyor belt and exit platform (left to right respectively). B: Conveyor belt with demarcation lines added.

Four conditions were tested, with the conveyor belt surface being either static or moving and with or without demarcation lines. For the no-demarcation condition, no markings were present on the belt surface (Figure 5.1A). For the demarcation condition, horizontal high contrast lines were added to the belt surface at equidistant 38cm intervals (Figure 5.1B), as per escalator step size (CIBSE, 2015). Participants were instructed to avoid foot contact with these demarcation lines when stepping onto the belt. Participants completed ten trials of each condition for a total of 40 trials, with the condition order randomised per participant. No failure to complete the task was observed in either age groups. Similar to previous research (Young, Wing, & Hollands, 2012) two younger, and seven older adults required the use of eye-glasses for daily locomotor activities so the collection of gaze data for these participants was not possible due to incompatibility with the gaze tracking equipment. All kinematic data was however collected for analysis from all participants.

5.3.4 Measures

Kinematic dependent variables

As per previous research (Chapman & Hollands, 2006) and consistent with best practice for gait data (Winter, 2009), raw kinematic data were processed using a low pass FIR digital filter at a cut off frequency of 6hz prior to model building and analysis. A CODA Pelvis model was then created using Visual 3D (C-Motion, 2018b). Key gait events (foot contact and toe off) were identified using a technique utilising the vertical acceleration of heel and toe markers (Hreljac & Marshall, 2000). Position and velocity data for the pelvic centre of mass (COM) in the anterior posterior direction (x), as well as penultimate step and final step times and positions were exported for analysis in MATLAB (MathWorks Inc, 2019). Two categories of dependent variables were then generated: (i) *approach variables*, which captured participant behaviours as they negotiated the walkway prior to stepping onto the moving surface; and (ii) *final step* *variables*, which captured behaviours as the participant transitioned between the walkway and belt surface.

The following measures were included to examine the approach: (i) *Perturbation magnitude* (cm), which was included to reflect the fact that larger perturbations have been associated with increased environmental demand or behaviour maladaptation (McAndrew et al., 2011). Specifically, this measure was calculated as the peak absolute difference between a hypothetical linear ‘unperturbed’ A-P pelvic COM trajectory and the actual pelvic COM trajectory during the approach phase (cf. Fajen & Matthis, 2014); (ii) *Approach time* (s) was the duration of the approach phase, classified as the period between movement initiation (identified as the moment that pelvic COM velocity was greater than 0.50 m.s^{-1}: Halliday et al., 1998), and foot contact with the belt surface; and (iii) *Toe distance* (cm), measured horizontally (as per: Madalena et al., 2018; Rietdyk & Rhea, 2006; Zietz, et al., 2011) as the distance between the belt surface threshold and the front edge of the foot. This variable was calculated using the supporting foot’s calcaneus marker position minus the length of the footwear, with measurement taken as the contralateral foot crossed the threshold between the end of the walkway and the start of the moving surface. A positive value indicated supporting foot placement before the threshold, whereas a negative value indicated supporting foot placement after the threshold.

The following locomotor variables were considered *final step* variables: (i) *Step length* (cm), which was defined as the anterior-posterior (A-P) distance between left and right calcaneus markers for the step ending with foot contact with the belt surface. (ii) *Step time* (s), was calculated as the duration between final foot contact with the walkway and foot contact onto the belt surface (Hsu et al., 2015). Consistent with previous methods, variability measures were also calculated using standard deviation for step length, step time, toe distance and approach time variables (Bruijn et al., 2011, 2013; Maki, 1997; Zietz et al., 2011).

Gaze dependent variables

To record gaze behaviours, participants who did not require corrected vision were fitted with eye tracking glasses (Tobii pro-glasses 2). Gaze data were collected at 50Hz via mobile eye tracking with the head to world transformation undertaken using optoelectronic motion capture. Gaze data (eye position and orientation) were treated using a low pass Butterworth filter with cut off frequency determined by an auto correlation function (Challis, 1999; Roithner et al., 2000). Missing gaze data of up to 10 frames (0.1 seconds) were filled via quintic spline interpolation (Hessels, Niehorster, Kemner, & Hooge, 2017; See: Chapter 4 for detailed method). The resultant gaze vector's floor intercept was used to compute: (i) *Look ahead distance (m),* was calculated for the duration of the approach phase as the mean A-P distance between the participant's eye (derived from the gaze origin point) and the gaze vectors floor intercept point; (ii) *Walkway gaze transfer (s),* was defined as the time difference between the final foot contact with the walkway surface and the last fixation on the location of this step; (iii) *Belt gaze transfer (s),* was defined as the time difference between the foot contact with the belt surface and the last fixation on the location of this step.

Area of interest (AOI) analysis was undertaken to understand how gaze was allocated for each condition. Consistent with previous research the percentage of the approach the point of gaze was within designated AOI's was calculated (Hildebrandt & Cañal-Bruland, 2020; Miyasike-Dasilva et al., 2011; Parr et al., 2020). Five areas as areas of interest were used to classify gaze locations: (i) *Walkway surface:* the area between the participant's starting position and the threshold of the belt surface; (ii) *Belt surface:* the surface of the conveyor belt, which started at the end of the walkway and ended with a transition onto a platform 3m from the walkway's threshold*;* (iii) *Penultimate step:* the location of the final step on the walkway before transitioning onto the belt surface; (iv) *Final step:* the location of the first step onto the belt surface; *(*v*) Other:* any gaze locations not captured by the other AOI's.

5.3.5 Statistical Analysis

Self-reported measures

A Mann-Whitney U test was used to determine differences between the participant groups self-reported measures. The use of non-parametric tests was considered necessary as the assumptions of normality, assessed using Shapiro-Wilk tests, had been violated. Effect sizes were as rank-biserial correlation (r_{rb}) (Kerby, 2014). Bayesian statistics were calculated to evaluate the difference between measures, with the Bayes factor interpreted using thresholds specified by Raftery (1995). Bayesian analysis was conducted using Jamovi (The Jamovi Project, 2020).

Perceptual-motor measures

Linear mixed-effect models were used to examine the perceptual-motor behaviours (Hoffman & Rovine, 2007). The analysis consisted of a (2 (Age-group [young adults, old adults]) x 2 (Surface [Static, Moving]) x 2 (Accuracy [No-demarcation, Demarcation]) design, with surface and accuracy as the within subject factors and age group as the between subject factor. Analysis was undertaken in r (RStudio Team, 2020) using the 'nlme'(Pinheiro et al., 2020), 'ggplot2' (Wickham, 2016) and 'pastecs' (Ibanez & Grosjean, 2018) packages and based on the procedure outlined by Field and colleagues (2012). Where data were non-normally distributed, significant effects were cross checked with robust ANOVAs based on trimmed means (Field et al., 2012; Mair & Wilcox, 2020; Thomas et al., 2021).

Area of interest analysis

Gaze data were coded based on AOI to help understand how gaze was allocated as participants negotiated environmental challenges (Miyasike-Dasilva et al., 2011; Parr et al., 2020). When considering AOI data, researchers are commonly interested in the proportion of time that a participant's point of gaze falls within a series of pre-determined locations. As such, proportion based AOI data sets can be classified as 'compositional' data (Aitchison, 1982) as they add up to a fixed total (e.g., 100%). The fundamentally different properties of compositional compared to unconstrained data has been shown to effect the analysis process (Aitchison, 1982; Chastin et al., 2015; Coenders et al., 2015). As a result, a set of procedures has been developed for the analysis of compositional data sets that will be adopted in the current study (Gupta et al., 2018).

To account for discrepancies that have been noted when standard approaches are applied to compositional data a compositional analysis approach was adopted. Compositional data analysis was undertaken in r (RStudio Team, 2020), using the package 'compositions' (van den Boogaart, Tolosana, & Bren, 2009) and SPSS (SPSS, version 24) and undertaken based on the approaches outlined in previous research (van den Boogaart & Tolosana-Delgado, 2013; Chastin et al., 2015; Gupta et al., 2018; Martín-Fernández, Daunis-I-estadella, & Mateu-Figueras, 2015). Geometric data were 'closed' to form compositions, transformed using isometric log ratios, after which 'standard' statistical techniques were applied (Gupta et al., 2018). Repeated measures multivariate analysis of variance (MANOVA) was applied to ilr-transformed data to determine the separate main effects of Age ([young adults, old adults]); Surface ([Static, Moving]); (Accuracy ([No-demarcation, Demarcation]) on areas of interest viewing. To interpret significant effects, a geometric mean bar plot was constructed using log-ratios (see: Gupta et al., 2018).

5.4 Results

5.4.1 Self-reported measures

Mann-Whitney U tests identified significant differences between age groups in the falls efficacy scale, and activities balance confidence measures. No other significant differences were found between age groups (Table 5.1). Bayes factors also indicated strong evidence for differences between age groups in measures of falls efficacy and activities balance confidence.

Table 5.1: Characteristics of younger and older adults

	Younger		Older					
	Mean	SD	Mean	SD	*U*	*p*	r_{rb}	BF_{10}
Fall Efficacy Scale (international)	18	1.41	20	2.27	40	0.014[a]	0.56	4.134
Activities Balance Confidence Scale	97.20	2.01	92.42	4.81	33	0.006[a]	0.63	11.394
MSRS Total	27.5	10.86	21.9	12.75	64.5	0.222	0.28	0.593
CMP	14.5	7.76	11.2	5.72	64.5	0.220	0.28	0.651
MSC	12.67	6.04	10.67	7.1	65.5	0.235	0.27	0.450

[a] Significant difference (p < .05) between age groups

Table 5.2: Age group and experimental condition comparisons for approach variables (Mean ± SD).

	Static		Moving	
	No Demarcation	Demarcation	No Demarcation	Demarcation
Perturbation Magnitude (cm)				
Younger	10.6 ± 2.8	10.6 ± 5.1	9.8 ± 1.9	9.0 ± 1.2
Older	12.2 ± 4.5	12.0 ± 6.0	10.3 ± 2.7	11.7 ± 3.5
Approach Time (s) [b, c, e]				
Younger	2.38 ± 0.25	2.47 ± 0.28	2.33 ± 0.26	2.42 ± 0.35
Older	2.53 ± 0.34	2.73 ± 0.29	2.45 ± 0.35	2.78 ± 0.38
Approach Time Variability (s) [c]				
Younger	0.08 ± 0.05	0.09 ± 0.05	0.11 ± 0.04	0.11 ± 0.07
Older	0.15 ± 0.06	0.15 ± 0.12	0.15 ± 0.15	0.19 ± 0.07
Toe Distance (cm) [a, b]				
Younger	17.8 ± 10.9	12.6 ± 9.8	11.5 ± 8.3	9.1 ± 9.2
Older	12.5 ± 7.7	8.7 ± 5.9	7.8 ± 5.9	4.0 ± 5.7
Toe Distance Variability (cm) [b, f]				
Younger	5.3 ± 4.0	3.8 ± 2.6	5.8 ± 3.2	2.7 ± 1.4
Older	6.7 ± 4.4	2.8 ± 1.7	4.6 ± 3.2	2.7 ± 0.8
Look Ahead Distance (m) [a, d]				
Younger	1.69 ± 0.73	2.21 ± 1.61	1.21 ± 0.43	0.99 ± 0.28
Older	1.57 ± 1.19	1.85 ± 1.13	1.55 ± 1.49	0.92 ± 0.31

[a] Significant difference (*p*<.05) between surface conditions See Table 4.
[b] Significant difference between demarcation conditions See Table 4.
[c] Significant difference between age groups See Table 4.
[d] Significant (*p* < .05) two-way interaction between surface and demarcation conditions. See Table 5.
[e] Significant two-way interaction between demarcation conditions and age. See Table 6.

5.4.2 Approach variables

Perturbation Magnitude No significant main effects were identified between surface conditions, demarcation conditions, or between age groups ($p>.05$, Table 5.2). There were no significant interaction effects (all $p>.05$, Tables 5.4,5.5,5.6).

Approach Time Significant main effects (Table 5.2) were identified between demarcation conditions ($p<.001$) and between age groups ($p=.042$). These results showed that approach time increased when participants were required to avoid demarcation lines, and when participants were in the older age group. There was a significant interaction effect between age and demarcation condition ($p= .007$; Table 5.5). The interaction effect showed that approach time was significantly greater in older adults stepping onto surfaces with demarcation lines. All other main or interaction effects were non-significant (all $p>.05$, Tables 5.4,5.5,5.6).

Approach Time Variability A significant main effect (Table 5.2) showed that older adults approach times were significantly more variable than younger adults ($p=.008$). There were no other significant main effects or interaction effects (all $p>.05$, Tables 5.4,5.5,5.6).

Toe Distance Significant main effects (Table 5.2) were identified between surface conditions ($p< .001$) and demarcation conditions ($p<.001$). These results showed that the distance between the toe and belt surface was significantly reduced when participants were required to step onto moving surfaces, and when participants had to avoid demarcation lines. There was no significant difference between subject, or interaction effects (all $p>.05$, Tables 5.4,5.5,5.6).

Toe Distance Variability A significant main effect (Table 5.2) showed toe distance variability was reduced when participants had to avoid demarcation lines ($p<.001$). There were no other significant main effects (*p*>.05, Table 5.4) or two-way interaction effects (all *p*>.05, Table 5.5) but a significant three-way interaction was identified (*p*= .041, Table 5.6). The three-way interaction effect evidenced that older adult's toe distance variability was reduced by a greater amount when stepping onto moving surfaces with demarcation lines.

Look Ahead Distance Significant main effects (Table 5.2) were identified between surface conditions (*p*=.004), showing that participant look ahead distance was reduced when stepping onto moving surfaces. A significant interaction effect was identified between surface and demarcation condition (*p*= .004) indicating that look ahead distance reduced when participants stepped onto moving surfaces whilst avoiding demarcation lines. There were no other significant main or interaction effects (all *p*>.05, Tables 5.4,5.5,5.6).

Walkway Gaze Transfer Significant main effects (Figure 5.2) were identified between surface conditions (*p*=.004) and between age groups (*p*=.008). These main effects showed that gaze was transferred earlier for all participants when stepping onto moving surfaces and that older adults transferred gaze away from the walkway step location earlier than younger adults.

There were no other significant main or interaction effects (all *p*>.05, Tables 5.4,5.5,5.6).

5.4.3 Final Step Variables

Table 5.3: Age group and experimental condition comparisons for final step variables (Mean ± SD).

	Static		Moving	
	No Demarcation	Demarcation	No Demarcation	Demarcation
Step Length (cm) [a, b]				
Younger	66.3 ± 10.3	59.5 ± 7.7	69.2 ± 7.9	68.1 ± 7.5
Older	60.3 ± 8.8	57.8 ± 8.7	66.2 ± 10.0	61.8 ± 8.7
Step Length Variability (cm) [a, d]				
Younger	4.8 ± 2.8	3.5 ± 1.6	7.2 ± 2.2	8.7 ± 2.2
Older	5.4 ± 3.3	3.38 ± 2.66	7.5 ± 2.7	8.6 ± 2.8
Step Time (s) [a, b]				
Younger	0.67 ± 0.13	0.64 ± 0.17	0.59 ± 0.07	0.57 ± 0.10
Older	0.62 ± 0.12	0.59 ± 0.18	0.54 ± 0.09	0.47 ± 0.12
Step Time Variability (s)				
Younger	0.18 ± 0.06	0.19 ± 0.09	0.17 ± 0.07	0.16 ± 0.05
Older	0.18 ± 0.08	0.17 ± 0.08	0.14 ± 0.06	0.17 ± 0.05

[a] Significant difference (p<.05) between surface conditions. See Table 4.
[b] Significant difference between demarcation conditions. See Table 4.
[c] Significant difference between age groups. See Table 4.
[d] Significant (p< .05) two-way interaction between surface and demarcation conditions. See Table 5.
[e] Significant two-way interaction between demarcation conditions and age. See Table 5.
[f] Significant three-way interaction between surface, demarcation conditions and age. See Table 6.

Step Length Significant main effects (Table 5.3) were identified between surface conditions (p< .001) and demarcation conditions (p=.004). These main effects indicated that step length increased when stepping onto moving surfaces but decreased when stepping onto surfaces with demarcation lines. No significant between-subject effect or interaction effects were identified (all p>.05, Tables 5.4,5.5,5.6).

Step Length Variability A significant main effect (Table 5.3) was identified between surface conditions (p< .001). This main effect evidenced that step length was more variable when stepping onto moving surfaces. There were no significant main effects between demarcation conditions or between age groups (both p>.05; Table 5.4). A significant interaction effect between surface and demarcation condition was identified (p= .003). This interaction effect evidenced that the increased step length variability identified in moving compared to static conditions was furthered when demarcations were present on the belt surface. All other interaction effects were non-significant (all *p*>.05, Tables 5.4,5.5,5.6).

Step Time Significant main effects (Table 5.3) were identified between surface conditions (*p*< .001) and demarcation conditions (*p*=.025). These main effects showed that step time decreased when participants stepped onto moving rather than static surfaces, and surfaces with, rather than without, demarcation lines. There was no significant between subject or interaction effects (all *p*>.05, Tables 5.4,5.5,5.6).

Step Time Variability No significant main, or interaction effects (all *p*>.05, Tables 5.4,5.5,5.6) were found.

Belt Gaze Transfer Significant main effects (Figure 5.3) were identified between surface conditions (*p*< .001) and between demarcation conditions (*p*=.044). These main effects showed that gaze was transferred later both when participants stepped onto moving rather than static surfaces, and surfaces with rather than without demarcation lines. There were no significant between-subject or interaction effects (all *p*>.05, Tables 5.4,5.5,5.6).

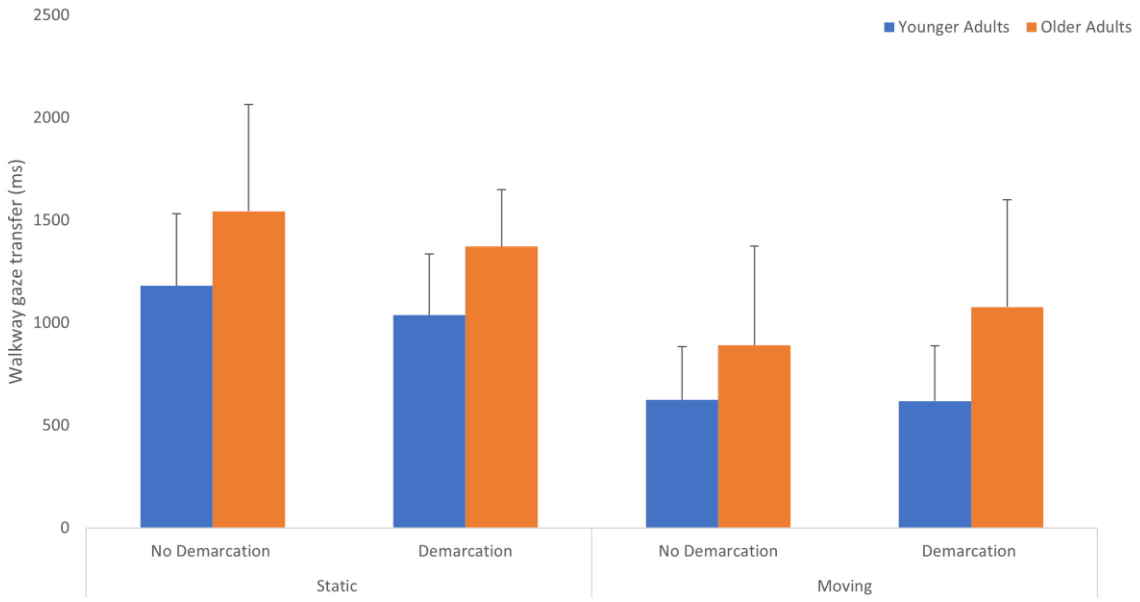

Figure 5.2: Walkway gaze transfer times, showing differences ($p<.05$) between age groups as well as between surface conditions. The fact all values are positive reflects all participants transferred gaze before the foot contacted the floor.

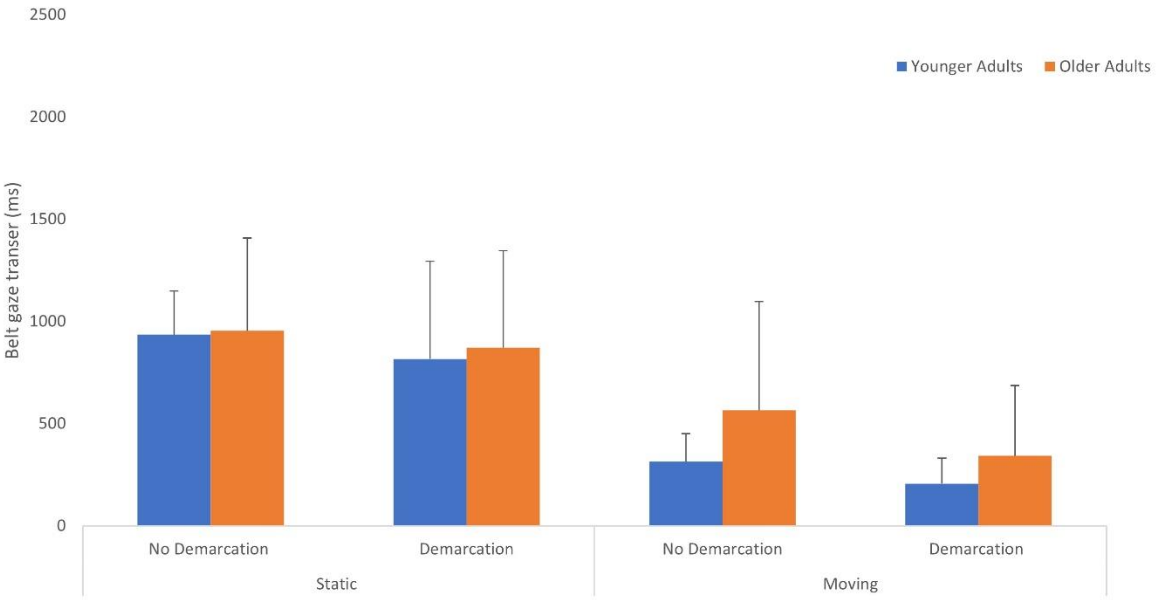

Figure 5.3: Belt gaze transfer times, showing differences ($p<.05$) between surface and demarcation conditions. The fact all values are positive reflects all participants transferred gaze before the foot contacted the floor.

Table 5.4: Main Effects

		Surface		Demarcation		Age Groups	
	DF	χ2	*p*	χ2	*p*	χ2	*p*
Perturbation Magnitude	1	2.536	0.111	0.049	0.825	2.312	0.128
Step Length	1	14.002	<0.001[a]	8.412	0.004[a]	2.724	0.099
Step Length Variability	1	41.139	<0.001[a]	0.160	0.689	0.095	0.758
Step Time	1	14.299	<0.001[a]	5.007	0.025[a]	2.970	0.085
Step Time Variability	1	2.159	0.142	0.160	0.689	0.304	0.581
Toe Distance	1	25.873	<0.001[a]	25.084	<0.001[a]	2.611	0.106
Toe Distance Variability	1	1.723	0.189	26.176	<0.001[a]	0.077	0.781
Approach Time	1	0.476	0.490	26.712	<0.001[a]	4.149	0.042[a]
Approach Time Variability	1	2.460	0.117	0.821	0.365	7.142	0.008[a]
Look Ahead Distance	1	8.196	0.004[a]	0.007	0.933	0.026	0.872
Walkway Gaze Transfer	1	20.586	<0.001[a]	1.157	0.282	7.054	0.008[a]
Belt Gaze Transfer	1	22.174	<0.001[a]	4.054	0.044[a]	0.928	0.336

[a] Significant difference ($p<0.05$) between conditions

Table 5.5: Two-way Interaction Effects

		Surface * Demarcation		Age * Surface		Age * Demarcation	
	DF	χ2	*p*	χ2	*p*	χ2	*p*
Perturbation Magnitude	1	0.126	0.722	0.006	0.938	0.415	0.519
Step Length	1	0.382	0.537	0.088	0.767	0.038	0.846
Step Length Variability	1	9.067	0.003[a]	0.018	0.894	0.314	0.575
Step Time	1	0.141	0.707	0.418	0.518	0.371	0.542
Step Time Variability	1	0.253	0.615	0.025	0.874	0.201	0.654
Toe Distance	1	0.865	0.352	0.013	0.908	0.000	0.995
Toe Distance Variability	1	0.179	0.672	0.635	0.426	0.372	0.542
Approach Time	1	1.445	0.229	0.415	0.520	7.290	0.007[a]
Approach Time Variability	1	0.435	0.510	0.016	0.901	0.747	0.388
Look Ahead Distance	1	8.135	0.004[a]	0.776	0.378	1.176	0.278
Walkway Gaze Transfer	1	0.165	0.684	0.558	0.455	1.854	0.173
Belt Gaze Transfer	1	0.160	0.689	0.774	0.379	0.149	0.700

[a] Significant difference ($p<0.05$) between conditions

Table 5.6: Three-way Interaction Effects

	DF	χ2	*p*
Perturbation Magnitude	1	0.653	0.419
Step Length	1	2.352	0.125
Step Length Variability	1	0.007	0.934
Step Time	1	0.243	0.622
Step Time Variability	1	1.460	0.227
Toe Distance	1	1.020	0.313
Toe Distance Variability	1	4.173	0.041[a]
Approach Time	1	0.960	0.327
Approach Time Variability	1	0.844	0.358
Look Ahead Distance	1	0.080	0.777
Walkway Gaze Transfer	1	0.028	0.868
Belt Gaze Transfer	1	0.471	0.492

[a] Significant difference ($p<0.05$) between conditions

5.4.4 AOI Analysis Results.

A repeated measures MANOVA identified main effects for surface condition (F(1,15) 3.915, *p* =.029, η2 = .556) and a significant interaction effect between age group and surface condition (F(1,15) 8.334, *p*=.002, η2 = .735). Other main and interaction effects were not significant (*p*>.05). Univariate analysis between surface conditions identified significant differences in the isometric log ratio (ILR) of penultimate step location compared to all other AOI values (F(1,15) = 12.829, *p*=.003, η2 = .461). This result indicates that compared to static surface conditions, when stepping onto moving surfaces the percentage of the approach phase spent viewing the penultimate step location was significantly greater than all other AOI's (Figure 5.4).

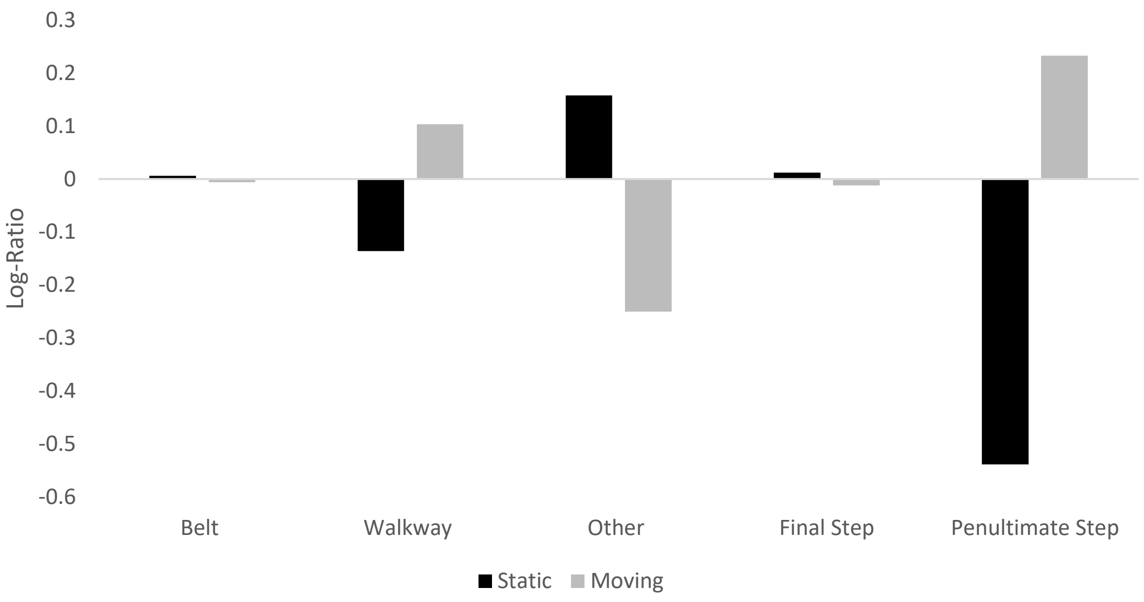

Figure 5.4: Areas of interest viewing ratios for static and moving belt conditions. The graph presents the geometric mean expressed in terms of a ratio measured on a logarithmic scale (as expressed on the y axis) to the geometric mean of the entire population for each area of interest. A ratio of 0 reflects that the groups geometric mean and the mean of entire population are equal. Positive and negative values show that the group geometric mean is larger and smaller than the entire population. On the basis of the log ratios displayed in the figure, the actual ratio of the geometric group mean to the whole group geometric mean can be calculated by taking the exp of the value from 100. For example, the bar corresponding to Penultimate step location in the static condition is negative (-0.54). This means that, on average, in the static condition participants spent 41.7% (100-exp of −0.54) less time looking at the walkway foot position than the whole group.

To further explore this main effect, the log ratio for each AOI was plotted for both surface conditions (Figure 5.4). Consistent with the results of the univariate analysis, the plot reinforces that the greatest difference between static and moving surface AOI viewing behaviours was observed within the penultimate step area. This suggests the penultimate step location was prioritised when stepping onto moving surfaces.

Univariate analysis identified a significant interaction effect in the ILR ratio of belt to walkway viewing percentages between surface condition and age group (F(1,15) = 9.062, *p*=.012, η2 = .350). To explore this effect, the log ratio for walkway and belt was plotted for each age group in both static and moving conditions (Figure 5.5). The log-ratio plot indicated that younger adults attended to the walkway more in the moving conditions compared to the static conditions. In contrast, older adults attended to the walkway less in moving conditions compared to static conditions.

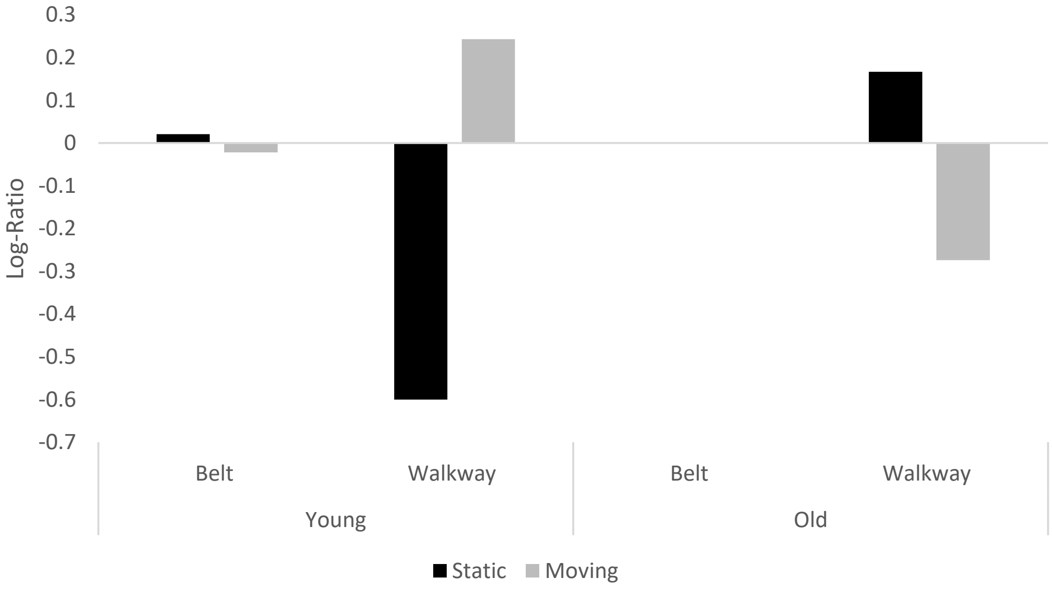

Figure 5.5: Geometric means expressed terms of a ratio measured on a logarithmic scale. The areas of interest incorporated within the isometric log ratio of Belt and Walkway areas have been plotted to allow identification of significant interaction effect.

5.5 Discussion

Affordance based control proposes that locomotion is shaped by the relationship between an individual's action capabilities and environmental demand (Fajen, 2007). This study developed a novel experiment with the aim of investigating the adaptive locomotor behaviours of younger and older adults as they negotiated static and moving surfaces, with and without accuracy demands denoted by demarcation lines. It was hypothesised that younger and older adults would control movement differently to achieve successful locomotion when overcoming increased environmental challenge. In particular it was expected that younger adults would use both online and feed-forward modes of control, whereas older adults would prioritise feed-forward control. In support of this hypothesis, results indicated that stepping onto moving surfaces, and surfaces with demarcation lines (in both surface conditions), resulted in older adults prioritising feed-forward control. That is, results revealed an increase in approach time, an increase in approach time variability and earlier gaze transfer from the walkway step in older adults. Such behaviours are in accordance with extant research suggesting that older adult prioritisation of distal constraints reflects a neglect of current stepping constraints and thus is a behaviour associated with increased fall risk (Chapman & Hollands, 2007; Ellmers et al., 2020; Young & Hollands, 2012).

As affordance based control stipulates environmental demand influences behaviour (Fajen, 2007), the current study compared older and younger adult behaviours across the different experimental conditions. Aligning with the second hypothesis, gait and gaze behavioural adaptations associated with increased environmental demand (e.g., moving and demarcation conditions) were identified. However, rather than 'cautious gait' behaviours emerging in demanding conditions, stepping onto moving surfaces invited different behavioural adaptions to conditions that demanded accuracy. Specifically, different gait (step length, step length variability, toe distance variability and approach time) and gaze (look ahead distance and walkway gaze transfer) adaptations were identified when participants overcame surface compared to demarcation conditions and will be discussed in greater detail during the discussion (see Tables 5.2 and 5.3). Overall, these findings build on extant perceptual-motor control literature and affirm that the synergistic relationship between online and feed-forward control (Matthis et al., 2017) promotes successful locomotion even when accurate movement is not demanded.

5.5.1 Behaviour as a function of age differences

Successful locomotion is achieved by adapting behaviours to reduce perturbation (Higuchi, 2013; Moraes, Allard, & Patla, 2007). In the present study, a measure of perturbation magnitude, based on Fajen and Matthis’ (2014) minimum velocity concept was developed, to calculate the peak distance between participant COM trajectory and a projected linear approach trajectory. No significant main or interaction effects for this measure were found, suggesting a level of successful locomotion was maintained by all participants in all conditions. This finding therefore may be in contrast to evidence that older adults are at risk of falling when negotiating moving surfaces, or environments that demand accuracy (Domínguez-zamora et al., 2020; Schminke et al., 2013; van Andel et al., 2018). Studies investigating different age groups have noted greater performance disparity between healthy younger adults and high fall-risk older adults, with comparatively fewer differences identified between young adults and low fall-risk older adults (Chapman & Hollands, 2007; Kovacs, 2005; Uiga et al., 2015). A likely explanation of the perturbation magnitude measure is that the older adult participants were of a low fall-risk group.

In extant literature, falls history is commonly utilised to classify high fall-risk participants (Ellmers, et al., 2020). However, due to safety requirements, it was necessary that all participants in the current study declared no history of falls. Movement reinvestment results did not differ between age groups, suggesting that older adults did not self-report as consciously controlling their movements, which is a behaviour associated with a reduction in high risk older adults performance (Malhotra et al., 2015; Uiga et al., 2020; Uiga et al., 2018). Despite this, the other older adult questionnaire results showed significantly greater FESi and reduced ABC measures compared to younger adults. Furthermore, Bayes values (4.13 and 11.39 for FESi and ABC respectively) supported suggestions from previous research that ABC measurements are more sensitive to falls anxiety in low risk older adults than FESi (Powell & Myers, 1995). Overall, whilst collective results indicate that the older adult participants represented a low-fall risk group, questionnaire differences between younger and older adults indicate that there was a reduction in self-report action capabilities with advancing age between the two participant groups (Chapman & Hollands 2007; Young & Hollands 2012).

Consistent with the interpretation of self-report measures considered, despite the perturbation magnitude measure indicating that older and younger adults maintained successful locomotion, results from the other variables indicate that perceptual-motor control differed between the two participant groups. Irrespective of condition, older adults demonstrated significantly longer approach times and an increase in approach time variability. A significant interaction effect further revealed that older adults increased their approach times more than younger adults when accuracy was demanded. Moreover, a significant three-way interaction revealed that older adult toe distance variability was reduced by a greater amount when stepping onto moving surfaces with demarcation lines. These adaptations indicate that the older adults utilised increased feed-forward control to overcome environmental demand (Barton et al., 2017; Chapman & Hollands, 2007; Domínguez-Zamora et al., 2020; Higuchi 2013; Matthis et al., 2017). This interpretation is further supported by the gaze behaviour results, which revealed that older adults transferred gaze from the walkway footstep location earlier than younger adults and viewed the walkway AOI less than younger adults in the moving surface conditions.

Utilising online control has been noted as more physically and cognitively demanding than feed-forward control (Ellmers et al., 2020; Ellmers & Young, 2019; Holtzer et al., 2015; Wagshul et al., 2019). As highlighted, the older adults self-reported fall related anxiety indicates a reduction in action capability compared to younger adults, thus online control may force older adults closer to the limits of their action boundaries (Fajen, 2007; Young & Hollands, 2012). As such, feed-forward behaviours indicated older adults exploited the gait cycle’s dynamics to ballistically adapt movements in advance; inviting successful locomotion at lower physical and cognitive demand (see: Muir et al., 2015). Aligning with affordance-based control, such adaptations suggest older adults utilised feed-forward control to reconcile reduced capabilities, thus indicating adaptive behaviours were scaled to action capabilities (see also: Parr et al., 2020).

When an individual’s capabilities are exceeded (e.g., by environmental demand), behavioural maladaptation may occur, increasing fall risk (Clark, 2015). Although all participants maintained successful locomotion, older adult adaptations corresponded to behaviours previously considered maladaptive such as significantly earlier gaze transfer and increased approach times. These adaptations are commonly associated with older adults recognised as high fall risk (Almarwani et al., 2016; Bhatt et al., 2005; Chapman & Hollands 2007). Specifically, earlier gaze transfer has been associated with reduced step placement accuracy (Chapman & Hollands, 2007) which in the context of stepping onto a moving surface, where older adults consistently positioned their feet closer to the approach walkway and moving surface threshold (Table 5.2), may increase the potential for the supporting foot of older adults to overlap the join between approach and moving surfaces, leading to a potential loss of balance. Furthermore, when accuracy was demanded, older adults increased their approach time more than younger adults. Previous research has noted increased approach times may reflect participants adopting behaviours that promote certainty when negotiating environments they find more challenging (Matthis et al., 2018). Accordingly, the different behaviours recorded between age groups suggests the increased environmental demand stipulated by experimental conditions may have forced older adults closer to the limits imposed by their action boundaries, thus inviting behaviour adaptation (Fajen, 2005). That is to say, the adaptive behaviours suggest that action capabilities appeared to be scaled to environmental demand (see also: Thompson et al., 2017).

The three-way interaction effect between age, surface, and accuracy conditions for toe distance variability highlights the interplay between action capability, environmental demand, and behaviour. Specifically, variability of the distance between foot-step placement and the start of the moving surface was reduced in the most demanding condition (moving with demarcation lines), with the largest reduction occurring among older adults. Locomotor-pointing research suggests regulating the preceding footstep location enables people to manipulate the ballistic trajectory of the COM, thus efficiently controlling foot placement via feed-forward control (Barton et al., 2017; Matthis, et al., 2017). This result not only indicates that adaptive behaviour was scaled to action capability (e.g., older adults adopted feed-forward control), but also implies that behavioural adaptations were relational to environmental demand.

5.5.1 Behaviours as a function of environmental demand

Following the proposal of affordance-based control (Fajen, 2005), which stipulates behaviours are a function of environmental demand, hypothesis two suggested that ‘cautious gait’ behaviours (e.g., increased approach times and decreased step lengths) would emerge in more demanding (e.g., when the belt surface was moving or when accurate movement was required to avoid demarcation lines) conditions (Barton et al., 2019; Reynolds & Day, 2005;

Weerdesteyn et al., 2004). Results showed that cautious gait behaviours emerged when accurate movement was demanded in the demarcation line conditions with evidence of both online and feed-forward control emerging in both older and younger adults, indicating that these control modes were utilised synergistically when accurate movements were demanded (Barton, Matthis, & Fajen, 2017; Domínguez-Zamora & Marigold, 2019; Ellmers et al., 2020; Fajen & Warren, 2007; Matthis et al., 2017; Matthis et al., 2018). Specifically, in demarcation line conditions, there was evidence for increased online control for both older and younger adults as indicated by reductions in the final step measures of step length and step time as well as later gaze transfer from the belt step location. Increased feed-forward control for both older and younger adults was also demonstrated by reduced kinematic measures of toe distance variability and increased approach times.

However, online and feed-forward behaviours were also recorded for both older and younger adults when adapting to the moving, compared to static surface conditions (e.g., moving surfaces with demarcations and without demarcations, compared to static surfaces with demarcations and without demarcation conditions). Specifically, older and younger adults demonstrated kinematic adaptations (including increased step length, step length variability, and reduced step time); and gaze adaptions (later gaze transfer from the belt footstep location), which indicated online control was utilised to actively guide the foot contacting the moving surface, irrespective of whether demarcation lines were present or not. Representative of increased feed-forward control, reduced look ahead distance, later walkway gaze transfer, and prioritisation of the penultimate step were also identified for both younger and older adults in the moving surface conditions.

Aside from demonstrating that the application of locomotor pointing paradigms apply to person-environment interactions occurring throughout everyday life (Lappi & Mole 2018; van Andel et al., 2018), the online and feed-forward adaptations exhibited in the moving surface conditions promoted successful locomotion for both younger and older adults (see also: Higuchi, 2013). Supporting this conclusion, previous research studied participants who were exposed to mechanically elicited backwards balance loss[11] and found an increased step speed (and associated COM velocity adaptation) was prominent in promoting stability (Bhatt et al., 2005; Espy et al., 2010). The current study's findings of reduced step time and increased step length for both older and younger adults when stepping onto moving surfaces, compared to static surfaces (regardless of demarcation condition, Tables 5.3 and 5.4) indicated that step speed increased. As these adaptations occurred during the concurrent step onto the moving surface, they reflect online control (Barton et al., 2019). However, consistent with behaviours associated with feed-forward control, the findings reflected increased attention to, and later gaze transfer from, the final walkway step location. These results indicate that both young and old adults adapted their approach to reduce the demand of the subsequent, potentially stability enhancing, adaptations. Accordingly, such findings support that the synergistic relationship between online and feedforward control (Matthis et al., 2018) is not limited to promoting accuracy but allows both older and younger adults to overcome the demands of stepping on to a moving surface.

Returning to cautious gait, significant main effects were identified between surface conditions and between demarcation conditions for the measure of step length (Table 5.4). These main effects highlight that the adaptive behaviours participants used to overcome static compared to moving surfaces differed to the adaptive behaviours used to overcome conditions that do and do not demand accuracy. Specifically, consistent with cautious gait, step length was reduced when both older and younger adults negotiated conditions with (rather than without) demarcation lines, however, inconsistent with cautious gait, step length was increased when

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[11] Researchers used a forward moving floor plate to provoke a slip like response, not dissimilar to stepping onto a moving surface.

participants negotiated conditions with moving (rather than static) surfaces (Swart et al., 2020; Thomas et al., 2020). That is to say, the step lengths of both younger and older adults were shortest when stepping onto static surfaces with demarcation lines and greatest when stepping onto moving surfaces without demarcation lines (Table 5.3). Gaze adaptations recorded between moving surface and static surface conditions differed to those recorded between demarcation and no demarcation conditions for both older and younger adults. Specifically, AOI analysis highlighted that penultimate step viewing was greater in conditions with moving surfaces, compared to conditions with static surfaces, however, viewing of the penultimate step location was not significantly different in conditions with demarcation lines compared to conditions without demarcation lines. That is to say, when overcoming moving surface conditions compared to static surface conditions both older and younger adults prioritised the penultimate step location, whereas viewing of this location was not adapted when participants negotiated demarcation compared to no demarcation conditions. Similarly, gaze was transferred away from the walkway step location later for both older and younger adults, when stepping onto conditions with moving rather than static surfaces, but this measure was not significantly different when comparing conditions with and without demarcation lines. Although the prediction of cautious gait behaviours was not confirmed for both older and younger adults, consistent with findings described earlier in the discussion (e.g., toe distance variability), results showed that behaviours differed between environmental demands. Moreover, significant two way interaction effects (i.e., for both young and old adults) were identified between surface and demarcation conditions for step length variability and look ahead distance measures (Table 5.5). Specifically, the moving surface condition with demarcation lines invited increased step length variability and reduced look ahead distances compared to other experimental conditions. Such adaptations indicated that the most demanding experimental condition invited specific behaviour adaptations in younger and older participants.

The emergence of distinct behaviour adaptations between experimental conditions (e.g., increased or reduced step length observed in moving vs static conditions, or demarcation vs no demarcation conditions respectively) indicated that the demands of the environment invited specific adaptive behaviours. That is to say, the behaviour adaptations underpinning successful location when stepping onto moving surfaces differed to those that afford successful locomotion in conditions that demand increased accuracy (Domínguez-Zamora et al., 2018; Higuchi, 2013; Matthis et al., 2018; Swart et al., 2020). Taken together, these findings align with recent perspectives (Withagen, Araújo, & de Poel, 2017; Withagen, de Poel, Araújo, & Pepping, 2012), which have proposed that the environment invites specific behaviours. Further, work aiming to promote safe behaviours may wish to consider if environments can be designed to invite beneficial locomotor adaptation, such as feed-forward control, which affords successful locomotion at a reduced physical demand (Barton et al., 2019). Such invitations for action may be particularly beneficial for older adults, who have been noted as having a reduced physical capacity. For example, changing the characteristics of an environment has been shown to have some potential for inviting ‘safer’ locomotor behaviours in older adults (Zietz et al., 2011) and merits further investigation within different challenging environments.

5.6 Conclusion

In conclusion, the current study found that older adults appeared to utilise feed-forward control more than younger adults. For example, older adults exhibited behaviours associated with feed-forward control, such as earlier gaze transfer from the walkway footstep location, and reduced viewing of the walkway AOI compared to younger adults in conditions with moving, rather than static surfaces. As different physical and cognitive demands are associated with online and feed-forward control (Barton et al., 2019), exploiting feed-forward control may have allowed the older adults to reduce the physical demands of successful locomotion, in turn suggesting adaptive behaviours were scaled to action capabilities.

To further explore the role of environmental demand on human behaviour, the adaptive behaviours that facilitated successful locomotion when older and younger participants overcame conditions with moving or static surfaces were compared to those that facilitated successful locomotion when overcoming conditions with or without demarcation lines. Results suggest that in all experimental conditions successful locomotion was a product of synergistic online and feedforward control (Matthis et al., 2017). Importantly, despite behaviours associated with both control modes being identified, the adaptations that enabled both older and younger participants to successfully overcome the demands of different surface conditions (e.g., moving surfaces with or without demarcation lines compared to static surfaces with or without demarcation lines) differed to the adaptations observed as participants overcame different demarcation line conditions (e.g., demarcation lines with moving and static surfaces, compared to no-demarcation lines with moving and static surfaces). The divergent behaviours suggest that adaptive behaviour was scaled to environmental demand and that environmental requirements invited specific behavioural adaptations. Moreover, by highlighting that adaptive behaviours are specific to the challenge being overcome, these findings support the need to examine perceptual-motor behaviours using paradigms that represent the range of locomotor challenges encountered during daily activity (Lappi & Mole; van Andel et al., 2018).

This study has highlighted three main implications for future research. Firstly, because the older adult participant group represented a low fall risk population, future work may benefit from considering how the behaviours of high fall risk older adults, with presumably lower action capabilities, may differ from younger adults or low fall risk older adults when stepping on to conditions with moving surfaces and/or accuracy demands. Secondly, the divergent adaptations observed between conditions with moving or static surfaces and conditions with or without demarcation lines, reinforce the importance of accurately sampling the diverse range of human environment interactions. Finally, as environmental requirements (e.g., surface or demarcation conditions) invited specific behaviour adaptations, future work may wish to explore if environmental design can invite beneficial behavioural adaptations that may reduce incident rates as people step onto moving surfaces.

CHAPTER 6: ACTION CAPABILITIES INFLUENCE THE EFFECTIVENESS OF DESIGN BASED BEHAVIOURAL INTERVENTIONS TO SOLICIT SAFER LOCOMOTOR BEHAVIOURS WHEN STEPPING ONTO MOVING SURFACES

6.1 Abstract

Stepping onto moving surfaces presents a challenge frequently encountered during daily locomotion. To counter heightened incident frequency and severity, safety interventions (high contrast demarcation lines and foot targets) are applied to escalator step surfaces. However, empirical research has not yet established their effectiveness. The current study examines the capacity of these interventions to invite safer behaviours in younger and older adults.

Twelve younger (18-40 years, Male = 8) and 15 older adults (60-81 years, Male = 5) negotiated four moving surface conditions ranging from low contrast demarcation lines without foot targets to high contrast demarcation lines with foot targets. Perceptual-motor behaviours were recorded using integration of optoelectronic motion capture and mobile eye tracking.

A two (age group) x two (demarcation condition) x two (foot target condition) linear mixed model indicated that older adults were more perturbed than younger adults (between subjects p=.012), however, perturbation magnitude did not vary between conditions (within subjects, p>.05). Thus, all participants maintained an equivalent level of successful locomotion across all conditions. Significant interaction effects between high contrast demarcation line and foot target conditions suggested that increased visual salience (e.g., high contrast lines and/or foot targets) invited behaviours associated with feed-forward control for both younger and older adults, potentially enabling a level of successful locomotion to be maintained at reduced physical demand. Significant main effects indicated perceptual-motor adaptations differed between conditions: foot targets invited behaviours associated with online motor control, such as increased step time variability (means of 0.17s for conditions without foot targets and 0.19s for conditions with foot targets) and later gaze transfer from final foot placement location (gaze

was transferred 311ms and 583ms prior to foot contact for conditions with and without foot targets respectively) in both younger and older adults As online control infers increased cognitive and physical demand, foot targets may force both older and younger adults closer to the limits imposed by their action capabilities. Between-subject effects revealed older adults adapted their approach to a greater extent than younger adults with more variable approach times and increased penultimate footstep viewing, reflecting a preference for feed-forward control. Moreover, as interaction effects between age group, and foot target condition indicated that younger adults were drawn to solicitations for online control to a greater extent, the effectiveness of interventions that invite online behaviours, such as foot targets, may not be beneficial for populations with reduced action capabilities. Future research should evaluate whether interventions that invite safer behaviours via feed-forward control offer a means of improving escalator safety.

6.2 Introduction

The ability to overcome environmental challenges is a fundamental attribute of successful locomotion and a skill exploited during everyday person-environment interactions. Failing to overcome environmental challenges carries severe consequence, particularly among frail older adults, for whom falling is recognised as the leading cause of morbidity and mortality (Rubenstein, 2006b). Alongside the direct health risk to the casualty, injuries associated with falls entail significant financial cost and add pressure to the health services (Carter et al., 2001). Accordingly, reducing incident frequency throughout daily tasks has received widespread attention (Hausdorff, 2005b). Stepping onto moving surfaces, such as escalators, presents a locomotor challenge that has received limited empirical attention, despite being encountered by urban dwelling people and associated with increased fall frequency and consequence (Chapter 5; Hsu et al., 2015). Despite heightened injury rates, particularly among older adults (Schminke et al., 2013), research has yet to determine the effectiveness of escalator safety interventions.

Extrapolated from staircase research (Jacobs, 2016), design based interventions have been applied to promote escalator safety (d2e, 2018). In particular, high contrast demarcation lines and foot targets, are commonly applied to escalator steps to invite safer behaviours (CIBSE, 2015; d2e, 2018; SASP, 2016; Zimmerman & Deshpande, 1982). Despite their widespread use, the adapted behaviours solicited by these interventions have not yet been examined in moving surface environments. Such an absence has been previously acknowledged within staircase interventions, with researchers noting the importance of empirically evaluating factors that influence public safety (Foster et al., 2014; Simoneau et al., 1991). Although recent research has shown that interventions, such as high contrast demarcations, can invite behaviour change in participants negotiating a flight of stairs (Zietz et al., 2011), adaptive behaviours have been shown to be specific to the performance environment (Chapter 5; Swart et al., 2020; Thomas et al., 2021). In particular, different adaptations affording successful locomotion have been reported when participants negotiate static or moving surfaces (Chapter 5; Hsu et al., 2015). For example, Chapter 5 found that when stepping onto moving rather than static surfaces, irrespective of whether demarcation lines were present or not, both younger and older adults increased their step lengths, reduced the toe distance between the walkway and moving surface and looked away from footstep location later. These findings necessitate the requirement to accurately sample the performance environment and may undermine the ability to generalise safety interventions between staircase (static) and escalator (moving) environments (Araújo et al., 2007; Brunswik, 1956; Dicks et al., 2009; van Andel et al., 2018).

6.2.1 Environmental design and behavioural change

The opportunities for action an environment offers a person relative to their abilities have been conventionally termed affordances (Gibson, 1979). Since initial conceptualisation by Gibson, the definition of affordances has developed. For instance, Dreyfus and Kelly (2007) suggest that affordances are not mere possibilities for action but *invitations* for specific behaviours; a stance that has gained popularity (Bruineberg & Rietveld, 2014; Rietveld & Kiverstein, 2014; Withagen et al., 2012, 2017). Many examples of environments inviting specific behaviours exist (see: Norman, 2013), but perhaps the most relatable is failing to pass through a doorway due to pulling a push door. Thaler and Sunstein (2009) capture this phenomenon stating that flat door plates invite 'push me' whereas door handles invite 'pull me'.

Architectural experiments emphasise that environmental design can invite specific behaviours (Desmet & Hekkert, 2007, 2009; Thaler & Sunstein, 2009). Rietveld (RAAAF, 2014) aimed to address the health issues associated with the modern motionless lifestyle by reconceptualising the office work environment. Termed 'End of Sitting' (EoS), the reconceptualised workspace traded prolonged sitting for various supported postures. RAAAF hypothesised physical activity would increase as workers moved to locations that appeared more comfortable throughout the day. Subsequently, several studies compared workers behaviours in EoS and traditional office environments (Caljouw et al., 2017, 2019; Withagen & Caljouw, 2016). Supporting RAAAF's hypothesis, EoS increased participants physical activity without negatively impacting productivity or work satisfaction, which highlighted the effectiveness of environmental design to invite healthier behaviours.

6.2.2 Action capabilities and inviting healthier behaviours

Despite establishing that environmental design can solicit behavioural adaptation, removing affordances (e.g., EoS trading sitting for supported standing) neglects to acknowledge people's ability to choose their own actions is an important aspect of human behaviour (Thaler & Sunstein, 2009; Withagen et al., 2012, 2017) and can be considered paternalistic[12]. Accordingly, design interventions like EoS potentially fail to recognise the varying needs of individuals or subpopulations (Barton & Grüne-Yanoff, 2015; Guala & Mittone, 2015; Hansen, 2016). Following this theme, research has identified differing person-EoS interactions. For instance, in a study comparing different age group behaviours, Caljouw and colleagues (2019) reported younger participants favoured locations that afforded a reclined posture (e.g., lying on their belly, back, curled-up, or bridging a gap with their feet against opposite walls), yet these locations were rarely used by middle-aged adults, who preferred supported leaning (see also: Zietz et al., 2011). These results indicate that different individuals are drawn to different behaviours, despite working in the same physical environment; a characteristic often related to an individual's distinct action capabilities (Gibson, 1996; Rietveld & Kiverstein, 2014; Withagen et al., 2012, 2017).

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[12] Paternalism has been defined as an action that limits a person's or group's liberty or autonomy and is intended to promote their own good (Dworkin, 2020; see also: Hansen, 2016).

The differing behaviours between age groups interacting with EoS can be evaluated by considering agency. Originally, agency positioned that people were not ‘pushed around’ by their environment but regulated their behaviours (Reed, 1996). However, Withagen and colleagues (2012, 2017) suggest the relationship between an individual’s action capabilities and environmental properties may better capture agency (see also: Kiverstein, van Dijk, & Rietveld, 2019). These factors not only determine possible actions (Fajen 2007, Warren, 1984) but how attractive affordances appear to an individual. Accordingly, Withagen and colleagues indicate that behaviours emerge from the interplay between the environment's invitations and the individual’s capacity to modulate the extent they are attracted, or resistant, to action. Building on the different behaviours solicited by EoS across age groups, agency provides a theoretical stance through which the behaviours invited by design interventions can be framed (Withagen et al., 2012). Therefore, considering the diverse range in action capabilities of people interacting with work (e.g., office), or public (e.g., escalator) environments is important when designing interventions to invite healthier behaviours.

6.2.3 Inviting safer adaptive locomotor behaviours

Redesigning the environment’s physical structure to solicit healthier behaviour (e.g., EoS) has been acknowledged as infeasible in some settings (CIBSE, 2015), with the environment’s structure posing constraints on available behaviours (Kiverstein et al., 2019). Both escalators and staircases fit into this category as they present the only means of mass pedestrian transport between a building’s floors (CIBSE, 2015). Instead, altering visual factors[13], such as increasing the visibility of step edges and including foot targets has been

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[13] Zietz, Johannsen and Hollands (2011) use the term visual factors to describe alterations to visually available information that does not alter the environments physical structure.

advocated and applied to promote safer behaviours on escalators (British Standards Institution, 2018; CIBSE, 2015; d2e, 2018).

Historically, research evaluating the manipulation of visual factors in locomotor settings has been recognised as scarce, with interventions informed by opinion, common sense, and anthropometry (Simoneau et al., 1991). Recently however, studies have reported that visual interventions can invite adapted behaviours (Foster et al., 2014; Iwata & Kitamoto, 2019; Thomas et al., 2021; Kim, 2009; Zietz et al.,2011). For example, Zietz and colleagues (2011) considered how high or low contrast stair edges influenced the kinematic behaviours of younger adults, older adults with low fall risk, and older adults with high fall risk when negotiating a staircase. The authors reported that younger adults increased the horizontal distance between foot and step edge, older adults with a low fall risk positioned their centre of mass (COM) further away from their anterior base of support, and older adults with a high fall risk reduced vertical COM acceleration variability. These findings led to the conclusion that high contrast edges led to adaptations associated with measures of posture and balance, which were particularly evident in higher risk older adults. Although Zietz and colleagues described the effects of stair edge contrast on younger and older adults and alluded to high contrast edgings having a beneficial effect on older adults balance control, the factors underpinning the different behavioural adaptations identified between conditions and age groups were not explored.

When overcoming environmental challenges, *online* and *feed-forward* control have been proposed to work synergistically to promote successful locomotion (Barton et al., 2017). Indications of online control include increased step length and step time variability as well as reduced walking smoothness, with such behaviours being observed when participants prioritise accurate foot placement or overcome challenging terrains (Chapman & Hollands, 2007; Matthis et al., 2018). Such adaptations indicate that visual information is used to regulate concurrent movement (Matthis, et al., 2018; Thomas et al., 2020). Conversely, feed-forward control uses distal visual information to adapt movements when approaching a constraint, exploiting the body's physical dynamics to alter step location whilst promoting accuracy, stability, and energetic efficiency (Barton et al., 2017; Ellmers et al., 2019; Higuchi, 2013; Uiga et al., 2015). Because the availability of visual information pertaining to the environment is a product of both the individual's visual acuity and the salience of visual information (Patla, 1996, 1998; Simoneau et al., 1991), Zietz and colleagues (2011) findings of reduced COM variability associated with posture and balance may suggest that high contrast lines invited participants to exploit feed-forward control (Barton, Matthis, & Fajen, 2017; Matthis, Barton, & Fajen, 2017; Muroi & Higuchi, 2017). Furthermore, the differing behaviours Zietz and colleagues (2011) reported between age groups aligns with research noting greater use of feed-forward behaviours amongst older adults (Chapman & Hollands, 2007; Chapter 5; Muir et al., 2015; Uiga et al., 2015; van Andel et al., 2018b).

However, only one study has explored gaze behaviours between different visual conditions. Thomas and colleagues (2021) investigated how stair surface properties, including high contrast edges, influenced perceptual-motor behaviours. The authors highlighted that with more complex step surface patterns or when edge highlighters were removed, maladaptive kinematic (e.g., reduced gait speed and foot clearance) and more proximal gaze behaviours emerged. The authors concluded that when visual characteristics were less salient, participants more actively searched for distal information. Dovetailing previous literature indicating stair edges invited adaptations associated with stability, posture, and balance (Zietz et al., 2011), Thomas and colleagues (2021) findings suggest that by including high contrast demarcation lines, participants were less dependent on actively searching for distal information and maintained greater stability. These adaptations are consistent with increased feed-forward control indicating that as information is more easily available, people are able to adapt their behaviours in advance.

6.2.4 The current study

The present investigation aims to address the lack of research studying the effect of visual-based safety interventions in moving surface environments. In particular, as Chapter 5 highlighted that participants (predominantly older adults) utilise feed-forward modes of control to overcome environmental challenges at reduced physical demand. Therefore, this chapter aims to consider if environmental design can reduce the demands of successful locomotion by inviting behaviours consistent with feed-forward control. As such, the first hypothesis suggests that increasing the salience of visual information via high contrast lines and/or foot targets, will reduce the demands of visually extracting distal information thereby reducing 'active search' behaviours whilst inviting feed-forward control (e.g., Thomas et al., 2021). Evidence supporting this hypothesis will emerge from gaze adaptations, such as reduced look ahead distance and time spent viewing the belt area of interest, with increased viewing time of, and later gaze transfer from, the final walkway step location in salient conditions. Because feed-forward control is associated with producing smoother and more stable locomotion at reduced demand (Barton et al., 2017; Barton et al., 2019; Ellmers et al., 2019), the emergence of feed-forward associated behaviours coupled with reduced or constant perturbation magnitude (e.g., Chapter 5) would signify that salient features reduced the demands associated with successfully stepping onto moving surfaces.

Secondly, because the environment invites actions (Caljouw et al., 2017; Swart et al., 2020; Withagen et al., 2017), it is expected that the behaviours solicited by demarcation and foot target conditions will differ. Specifically, if foot targets invite accurate movement, behaviours associated with increased online control, such as adapted step lengths and step times, may emerge (Barton et al., 2017; Matthis et al., 2018). As online control has been identified as more demanding, less stable, but more accurate (Ellmers et al., 2019; Matthis, Barton, & Fajen, 2015) foot targets may invite less successful (e.g., more perturbed or demanding) locomotion compared to conditions with no foot targets.

Finally, because older adults adopt feed-forward behaviours to reconcile reduced action capabilities and overcome challenges (Chapman & Hollands 2007; Chapter 5; Domínguez-zamora et al., 2020; Muir et al., 2015) and corresponding with contemporary accounts of agency (Withagen et al., 2012), it was expected that older adults will be more resistant to invitations that would necessitate an increase in online perceptual-motor control in order to act upon them.

6.3 Methods

6.3.1 Participants

The same twenty-seven participants who were recruited in Chapter 5 took part in this study. Research investigating adaptive locomotor behaviours (Chien et al., 2018; Ellmers et al., 2016; Matthis & Fajen, 2012, 2014; Matthis et al., 2015; Muroi & Higuchi, 2017) has reported large effect sizes (partial eta squared >0.14; Cohen, 1988) between 0.52 and 0.88 for comparable kinematic variables (e.g., approach time and step length) taken as participants negotiate different experimental conditions. Based on these values, an a priori power analysis was conducted for between factors using G*Power (Faul et al., 2007). The power analysis determined that a minimum of 12 participants per group would be required to obtain 80% power (Cohen, 1988).

The participants were grouped based on age boundaries used in previous research (Alcock et al., 2013; McCrum et al., 2017; Schminke et al., 2013). Younger adults (18 – 40 years, M = 26.5 SD = 5.7 years, *n* = 12, Male = 8) and older adults (60 years and older, M = 71.5 SD = 6.9 years SD = 5.7 years *n* =15, Male = 5) were recruited from the university and local community. To confirm differences between the two groups a questionnaire battery was administered as described in Chapter 5. Ethical approval was granted at an institutional level

(Appendix 1) with all participants providing signed consent, establishing no history of falling or physiological and neurological impairment.

6.3.2 Apparatus

Kinematic and gaze data were collected as outlined in Chapter 5.

6.3.3 Procedure

The experimental protocol was identical for all participants. Participants were instructed to walk along a two-metre walkway at their own pace, step onto a conveyor belt avoiding contact with demarcation lines (Figure 6.1) and stand on the belt surface until the end of the trial (trial duration was approximately 8 seconds). The walkway was flush with the conveyor surface, alleviating gait inconsistencies caused by changing surface height. A two-metre approach distance was selected based on distances found between start positions and targets or consecutive targets in locomotor research (Chapman & Hollands, 2006b; Uiga, Capio, Ryu, Young, et al., 2018), and recognising that people are commonly required to first negotiate another person or a barrier when using an escalator, meaning typical unconstructed approach distances of 2m (d2e, 2018). To promote a natural gait pattern the leading foot was not

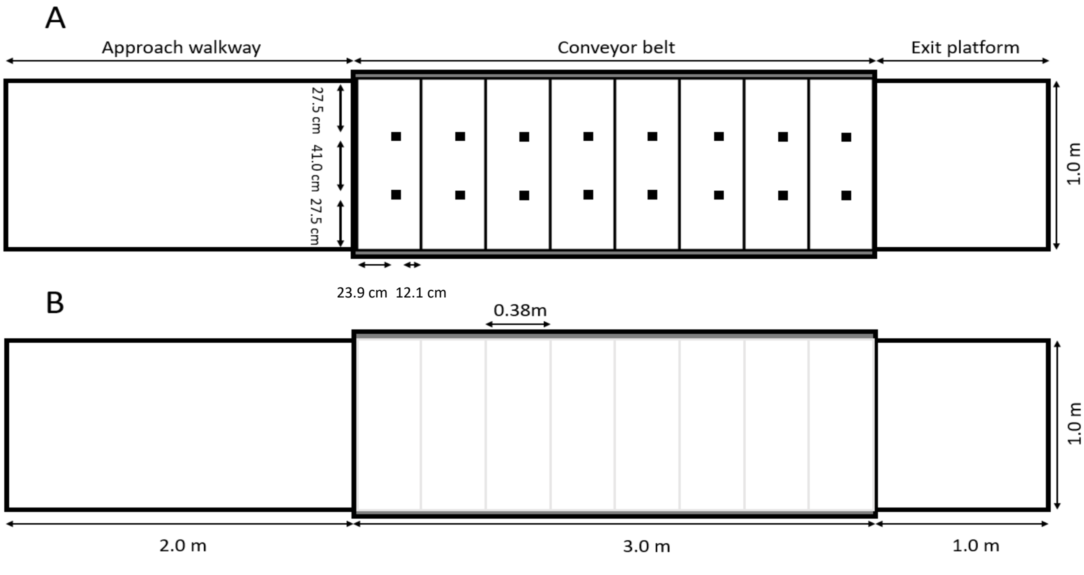

Figure 6.1: Top view of experimental task set up and dimensions. A: shows high contrast lines with foot targets; B: low contrast lines without foot targets.

regulated. Consistent with common escalator characteristics, the width of the conveyor belt was 1000mm, and the belt was set to a constant speed of $0.50m.s^{-1}$, to represent step boundaries horizontal lines were added to the belt surface at equidistant 38cm intervals, as per standard escalator step size (CIBSE, 2015).

Four conditions were tested, with (i) low contrast demarcation lines and no foot targets; (ii) low contrast demarcation lines and foot targets; (iii) high contrast demarcation lines and no foot targets; (iv) high contrast demarcation lines and foot targets. To form the contrast line conditions, 2 cm wide high (Figure 6.1A) or low (Figure 6.1B) contrast lines were added to the belt surface. Public building regulations (British Standards Institution, 2018) state that a minimum 30-point light reflective value difference between demarcations and the stair step must be present to represent a contrast. The mean of five spot luminance measures (Minolta SL110 Luminance meter) identified light reflectance (LRV) values of 4.2 (belt surface), 17.6 (low contrast demarcation) and 34.8 (high contrast demarcation). Foot targets were added to the belt surface using the same tape that formed the high contrast condition. Foot targets measured 2cm by 2cm and were positioned 12.1cm behind each 'steps' leading edge. Based on UK average shoulder width (Adler, 1999), the foot target centres were separated by 43cm, and centralised to the width of the belt. Although participants were asked to avoid contacting demarcation lines, as per stepping onto an escalator surface, no explicit instruction pertaining to foot target was provided. Participants completed ten trials of each condition for a total of 40 trials, with the order randomised per participant. No failure to complete the task was observed for any participant.

6.3.4 Measures

Kinematic dependent variables

Kinematic measurements were taken as per Chapter 5.

Gaze dependent variables

As per chapter 5, to record gaze behaviours participants who did not require corrected vision were fitted with eye tracking glasses (Tobii pro-glasses 2). Gaze data were collected at 50Hz via mobile eye tracking with the head to world transformation undertaken using optoelectronic motion capture. Gaze data (eye position and orientation) were treated using a low pass Butterworth filter with cut off frequency determined by an auto correlation function (Challis, 1999; Roithner et al., 2000). Missing gaze data of up to 10 frames (0.1 seconds) were filled via quintic spline interpolation (Hessels, Niehorster, Kemner, & Hooge, 2017). The resultant gaze vector's floor intercept was used to compute the approach variables of: *Look ahead distance (m),* was calculated for the duration of the approach phase as the mean A-P distance between the participant's eye (derived from the gaze origin point) and the gaze vectors floor intercept point; *Walkway gaze transfer (s),* was defined as the time difference between the final foot contact with the walkway surface and the last fixation on this steps location. The final step variable of *Belt gaze transfer (s)* was defined as the time difference between the foot contact with the belt surface and the last fixation on this steps location. Area of interest (AOI) analysis was undertaken to understand how gaze was allocated as participants completed the task. Consistent with previous research the percentage of the approach period point of gaze was within designated AOI's was calculated (Hildebrandt & Cañal-Bruland, 2020; Miyasike-Dasilva et al., 2011; Parr et al., 2020). The following five areas as areas of interest were classified: (1) *Walkway surface:* the area between the participant's starting position and the threshold of the belt surface; (2) *Belt surface:* the surface of the conveyor belt, which started at the end of the walkway and ended with a transition onto a platform 3m from the walkway's threshold*;* (3) *Penultimate step:* the location of the final step on the walkway before transitioning onto the belt surface; (4) *Final step:* the location of the first step onto the belt surface; *(5) Other:* any gaze locations not captured by the above AOI's.

6.3.5 Statistical Analysis

Self-reported measures

Statistical analysis for self-reported measure were performed as per Chapter 5.

Perceptual-motor measures

Linear mixed-effect models were used to examine the kinematic and gaze dependent variables (Hoffman & Rovine, 2007). The analysis consisted of a (2 (Age-group [young adults, old adults]) x 2 (Demarcation [Low contrast, High contrast]) x 2 (Target [No-Targets, Targets]) design, with Demarcation and Target as the within subject factors and age group as the between subject factor. Analysis was undertaken in r (RStudio Team, 2020) using the ‘nlme’(Pinheiro, Bates, DebRoy, Sarkar, & R Core Team, 2020), ‘ggplot2’ (Wickham, 2016) and ‘pastecs’ (Ibanez & Grosjean, 2018) packages and based on the procedure outlined by Field and colleagues (2012). Where data were non-normally distributed, significant effects were cross checked with robust ANOVAs based on trimmed means (Field et al., 2012; Mair & Wilcox, 2020; Thomas et al., 2021).

Area of interest analysis

Compositional analysis of area of interest based gaze data was undertaken as described in Chapter 5. Repeated measures multivariate analysis of variance (MANOVA) was applied to ILR-transformed data to determine the separate main effects of age (younger and older adults), demarcation (high contrast and low contrast demarcation lines), and foot target (foot target and no foot target) conditions for the viewing of the five areas of interest. To interpret significant effects, geometric mean bar plots were constructed using log-ratios (see: Gupta et al., 2018).

6.4 Results

6.4.1 Self-reported measures

As the same participants were tested as per Chapter 5 please refer to Chapter 5 to view these results.

6.4.2 Approach variables

Perturbation Magnitude No significant main effects were identified between conditions however a significant main effect (Table 6.1) was identified between age groups (p=.012). This result showed that irrespective of condition, older adults were more perturbed than younger adults. There were no significant interaction effects (all p>.05, Tables 6.4,6.5).

Approach Time Significant main effects (Table 6.1) were identified between age groups (p=.042). These results showed approach time was increased when participants were in the older age group. There were no significant interaction effects (all p>.05, Tables 6.4,6.5).

Table 6.1: Age group and experimental condition comparisons for approach variables (Mean ± SD).

	Low Contrast		High Contrast	
	No targets	Targets	No targets	Targets
Perturbation Magnitude (cm) [a]				
Younger	9.5 ± 2.0	8.3 ± 2.6	9.0 ± 1.2	9.8 ± 2.4
Older	13.8 ± 6.6	11.4 ± 3.4	11.70± 3.5	11.8 ± 5.4
Approach Time (s) [a]				
Younger	2.44 ± 0.33	2.43 ± 0.32	2.42 ± 0.35	2.48 ± 0.41
Older	2.84 ± 0.43	2.85 ± 0.42	2.78 ± 0.38	2.73 ± 0.42
Approach Time Variability (s) [a]				
Younger	0.12 ± 0.03	0.11 ± 0.04	0.11 ± 0.07	0.13 ± 0.05
Older	0.25 ± 0.23	0.21 ± 0.13	0.19 ± 0.07	0.15 ± 0.07
Toe Distance (cm)				
Younger	7.7 ± 7.4	7.4 ± 7.1	9.1 ± 9.2	8.2 ± 6.1
Older	4.1 ± 5.5	4.08 ± 4.9	4.0 ± 5.7	3.0 ± 4.2
Toe Distance Variability (cm)				
Younger	4.4 ± 4.0	3.7 ± 2.6	2.7 ± 1.4	4.1 ± 3.5
Older	2.7 ± 0.9	3.38 ± 4.0	2.7 ± 0.8	3.2 ± 1.3

[a] Significant difference (p<.05) between age groups

Approach Time Variability Significant main effects (Table 6.1) were identified between age groups (*p*=.009). These results showed approach time variability was increased when participants were in the older age group. There were no significant interaction effects (all *p*>.05, Tables 6.4,6.5).

Toe Distance No significant main or interaction effects (all *p*>.05, Tables 6.3, 6.4, 6.5) were found.

Toe Distance Variability No significant main or interaction effects (all *p*>.05, Tables 6.3, 6.4, 6.5) were found.

Look Ahead Distance Significant main effects (Table 6.3) were identified between demarcation conditions (*p*=.001) and foot target conditions (*p*=.002), showing that participants look ahead distance was reduced when stepping onto moving surfaces with (rather than without) high contrast lines or foot targets (Figure 6.2). A significant interaction effect was identified between demarcation and foot target condition (*p*<.001) evidencing look ahead distance was greatly reduced when younger and older participants stepped onto surfaces with high contrast demarcation lines and foot targets. There were no other significant main or interaction effects (all *p*>.05, Tables 6.3,6.4,6.5).

Walkway Gaze Transfer Significant main effects (Table 6.3) were identified between demarcation conditions (*p*=.007) and foot target conditions (*p*=.005), showing that participants gaze transfer was reduced when stepping onto moving surfaces with, rather than without, high contrast lines or foot targets (Figure 6.3). A significant interaction effect was identified between demarcation and foot target condition was identified (*p*<.001) evidencing gaze transfer was greatly reduced when participants stepped onto surfaces with, rather than without, both high contrast demarcation lines and foot targets. There were no other significant main or interaction effects (all *p*>.05, Tables 6.3,6.4,6.5).

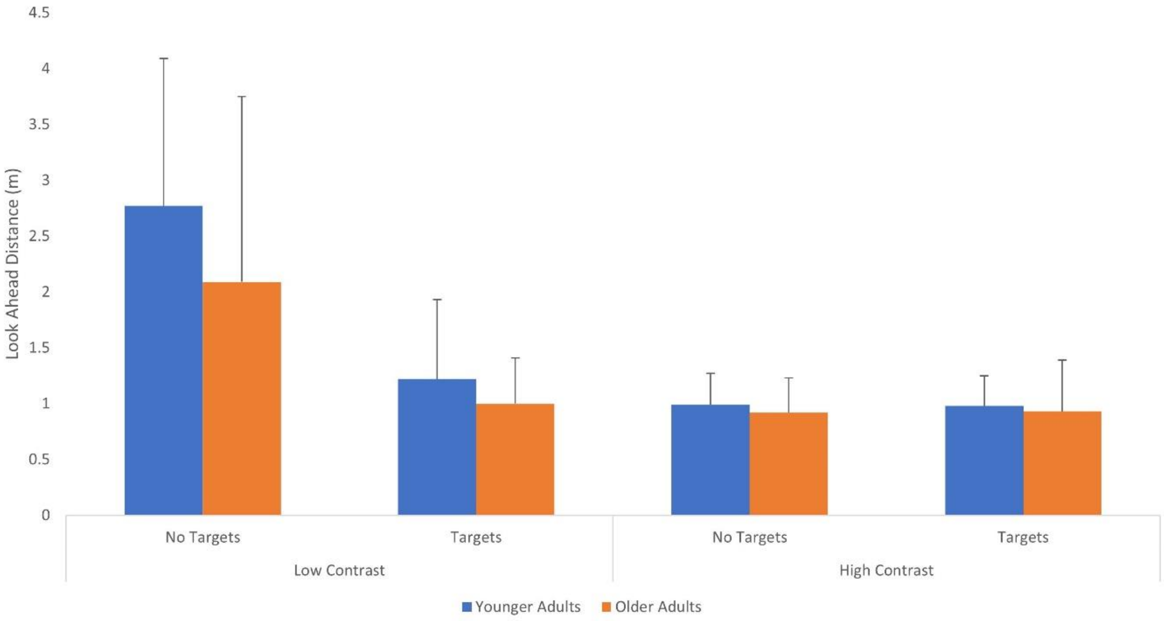

Figure 6.2: Younger and Older adults Look ahead distances across all experimental conditions. The figure highlights that when no salient features were presented on the belt surface (e.g., the low contrast and no target condition) participants look ahead distances were reduced.

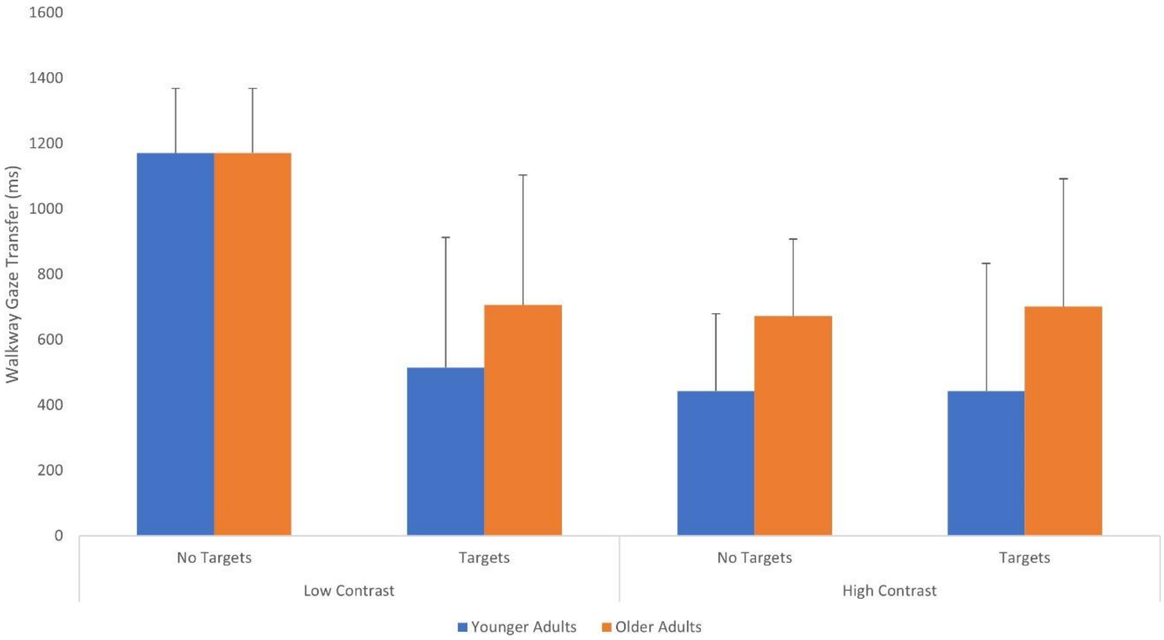

Figure 6.3: Younger and Older adults Walkway Gaze Transfer times across all experimental conditions. The figure highlights that when no salient features were presented on the belt surface (e.g., the low contrast and no target condition) participants looked away from the walkway footstep location earlier.

6.4.3 Final step variables

Table 6.2: Age group and experimental condition comparisons for final step variables (Mean ± SD).

	Low Contrast		High Contrast	
	No Targets	Targets	No Targets	Targets
Step Length (cm)				
Younger	68.1 ± 6.8	66.3 ± 5.7	68.1 ± 7.5	65.3 ± 6.4
Older	63.3 ± 7.5	62.4 ± 7.3	61.8 ± 8.7	63.7 ± 6.7
Step Length Variability (cm)				
Younger	10.4 ± 4.2	8.5 ± 3.0	8.7 ± 2.2	9.0 ± 4.3
Older	8.4 ± 2.1	10.3 ± 3.0	8.6 ± 2.8	8.92 ± 2.0
Step Time (s) [b]				
Younger	0.55 ± 0.12	0.50 ± 0.10	0.57 ± 0.13	0.53 ± 0.06
Older	0.50 ± 0.11	0.48 ± 0.11	0.47 ± 0.12	0.46 ± 0.13
Step Time Variability (s) [e,b]				
Younger	0.15 ± 0.05	0.18 ± 0.05	0.16 ± 0.05	0.21 ± 0.05
Older	0.18 ± 0.05	0.18 ± 0.04	0.17 ± 0.05	0.17 ± 0.05

[a] Significant difference ($p<0.05$) between demarcation conditions

[b] Significant difference between foot target conditions

Step Length No significant main, or interaction effects (all $p>.05$, Tables 6.3, 6.4, 6.5) were found.

Step length variability No significant main, or interaction effects (all $p>.05$, Tables 6.3, 6.4, 6.5) were found.

Step Time a significant main effect (Table 6.2) was identified between foot target conditions ($p= .035$). This main effects showed that step time was decreased when participants stepped onto surfaces with, rather than without foot targets. There was no significant between subject or interaction effects (all $p>.05$, Tables 6.3, 6.4, 6.5).

Step Time Variability a significant main effect (Table 6.2) was identified between foot target conditions ($p= .048$). This main effect showed that step time variability increased when participants stepped onto surfaces with, rather than without foot targets. There was a significant interaction effect between foot targets and age group ($p= .027$). The interaction showed that in comparison with older adults, step time was more variable in younger adults when stepping onto surfaces with foot targets. No other main or interaction effects were identified (all *p*>.05, Tables 6.3, 6.4, 6.5).

Belt Gaze Transfer Significant main effects (Table 6.3) were identified between demarcation conditions (*p*< .001) and foot target conditions (*p*<.001), showing that participants gaze transfer was reduced when stepping onto moving surfaces with high contrast lines or foot targets (Figure 6.4). A significant interaction effect was identified between demarcation and foot target condition (*p*<.001) evidencing gaze transfer was greatly reduced when participants stepped onto surfaces with, rather than without, high contrast demarcation lines and foot targets. There were no other significant main or interaction effects (all *p*>.05, Tables 6.3, 6.4, 6.5).

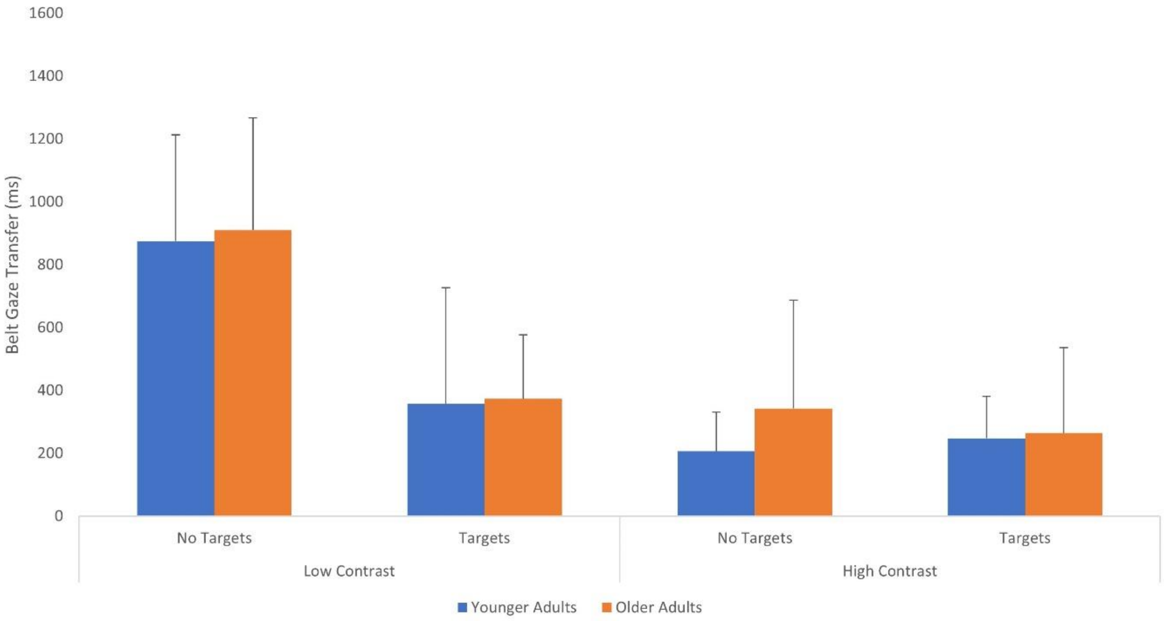

Figure 6.4: Younger and Older adults Belt Gaze Transfer times across all experimental conditions. The figure highlights that when no salient features were on the belt surface presented (e.g., the low contrast and no target condition) participants looked away from their final footstep location earlier.

Table 6.4: Main Effects

		Demarcation		Target		Age Group	
	DF	χ2	*p*	χ2	*p*	χ2	*p*
Perturbation Magnitude	1	0.266	0.606	0.782	0.376	6.305	0.012 [a]
Step Length	1	0.047	0.828	1.071	0.301	3.132	0.077
Step Length Variability	1	0.509	0.476	0.003	0.954	0.030	0.863
Step Time	1	0.030	0.863	4.437	0.035 [a]	3.310	0.069
Step Time Variability	1	0.099	0.753	3.894	0.048	0.012	0.912
Toe Distance	1	0.159	0.690	1.455	0.228	3.632	0.057
Toe Distance Variability	1	0.970	0.325	0.016	0.900	0.667	0.414
Approach Time	1	1.686	0.194	0.032	0.857	6.066	0.014 [a]
Approach Time Variability	1	2.565	0.109	1.599	0.206	6.738	0.009 [a]
Look Ahead Distance	1	12.503	0.001 [a]	9.990	0.002 [a]	1.531	0.216
Walkway Gaze Transfer	1	7.118	<0.001 [a]	7.906	0.005 [a]	3.779	0.052
Belt Gaze Transfer	1	18.636	<0.001 [a]	18.443	<0.001 [a]	0.049	0.825

[a] Significant difference (*p*<0.05) between conditions

Table 6.5: Two-way Interaction Effects

		Demarcation * Target		Age * Demarcation		Age * Target	
	DF	χ2	*p*	χ2	*p*	χ2	*p*
Perturbation Magnitude	1	2.257	0.133	0.641	0.423	0.773	0.379
Step Length	1	0.721	0.396	0.174	0.677	2.751	0.097
Step Length Variability	1	0.084	0.772	0.000	0.995	3.277	0.070
Step Time	1	0.001	0.973	1.778	0.182	1.029	0.310
Step Time Variability	1	0.025	0.874	2.423	0.120	4.871	0.027 [a]
Toe Distance	1	0.756	0.385	2.802	0.094	0.002	0.960
Toe Distance Variability	1	0.290	0.591	0.076	0.783	3.196	0.074
Approach Time	1	0.011	0.916	2.458	0.117	0.739	0.390
Approach Time Variability	1	0.124	0.725	2.245	0.134	2.105	0.147
Look Ahead Distance	1	11.525	<0.001 [a]	0.874	0.350	0.465	0.495
Walkway Gaze Transfer	1	15.921	<0.001 [a]	0.183	0.669	0.117	0.733
Belt Gaze Transfer	1	24.592	<0.001 [a]	0.000	0.987	0.218	0.641

[a] Significant difference (*p*<0.05) between conditions

Table 6.6: Three-way Interaction Effects

	DF	χ2	*p*
Perturbation Magnitude	1	0.174	0.676
Step Length	1	1.827	0.176
Step Length Variability	1	3.144	0.076
Step Time	1	0.004	0.952
Step Time Variability	1	0.199	0.655
Toe Distance	1	0.009	0.924
Toe Distance Variability	1	2.431	0.119
Approach Time	1	1.143	0.285
Approach Time Variability	1	0.452	0.501
Look Ahead Distance	1	0.367	0.545
Walkway Gaze Transfer	1	0.921	0.337
Belt Gaze Transfer	1	0.298	0.585

[a] Significant difference (*p*<0.05) between conditions

6.4.4 AOI Analysis Results.

A repeated measures MANOVA identified main effects for demarcation conditions (F(1,15) 5.107, *p* =.012, η2 = .630) and target conditions (F(1,15) 12.569, *p* <.0001, η2 = .897). A significant interaction effect between demarcation and target conditions (F(1,15) 3.880, *p*=.030, η2 = .564) was also identified. Follow up univariate analysis comparing demarcation contrast conditions identified a significant reduction in the isometric log ratio (ILR) of the 'other' AOI compared to the belt and walkway AOIs (F(1,15) = 3.706, *p*=.025, η2 = .198) and a greater ILR on the penultimate step AOI compared to all other AOI values (F(1,15) = 8.954, *p*=.009, η2 = .374; Figure 6.5A) in the high contrast condition. Between foot target conditions, univariate analysis identified significant increase in final step (F(1,15) = 4.840, *p*=.044, η2 = .244) and penultimate step (F(1,15) = 54.277, *p*<. 0001, η2 = .783) ILR viewing (Figure 6.5B) when foot targets were added to the belt surface. A significant between subjects effect was identified (6.5C) highlighting that irrespective of experimental condition older adults exhibited greater viewing of the penultimate foot step AOI compared to younger adults (F(1,15) = 6.220, *p*=.025, η2 = .293). The interaction between demarcation and target conditions was explored using univariate analysis, with significant effects identified between other (F(1,15) = 7.268, *p*=.017, η2 = .326); penultimate step (F(1,15) = 15.804, *p*=.001, η2 = .513); and final step (F(1,15) = 4.946, *p*=.042, η2 = .248) AOI locations being identified. These results suggest: (i) viewing of other AOI increased when participants stepped onto surfaces with low contrast lines and no foot targets; (ii) viewing of final step AOI decreased when participants stepped onto surfaces with low contrast lines and no foot targets; (iii) viewing of penultimate step AOI decreased when participants stepped onto surfaces with low contrast lines and no foot targets (Figure 6.6).

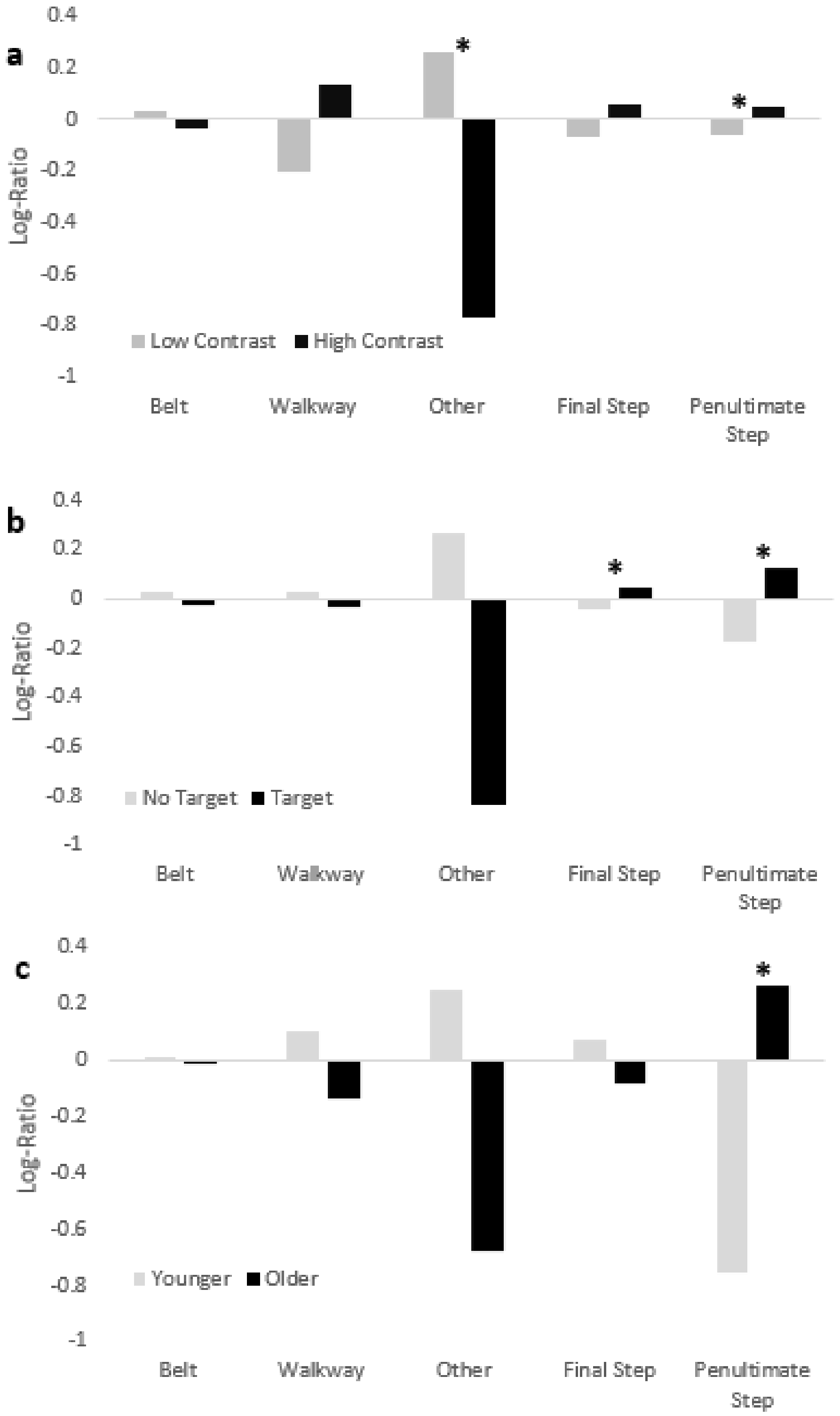

Figure 6.5: Area of interest viewing ratios for High and Low contrast demarcation conditions (top); No target and Target condition (middle); Younger and Older adult age groups (bottom). The graphs present the geometric mean of each condition expressed in terms of a ratio of the geometric mean, measured on a logarithmic scale. A ratio of 0 reflects each group is equal, positive, or negative values show the geometric mean is larger or smaller respectively than the population mean. Asterix (*) denotes significant difference (*p*<.05) between groups.

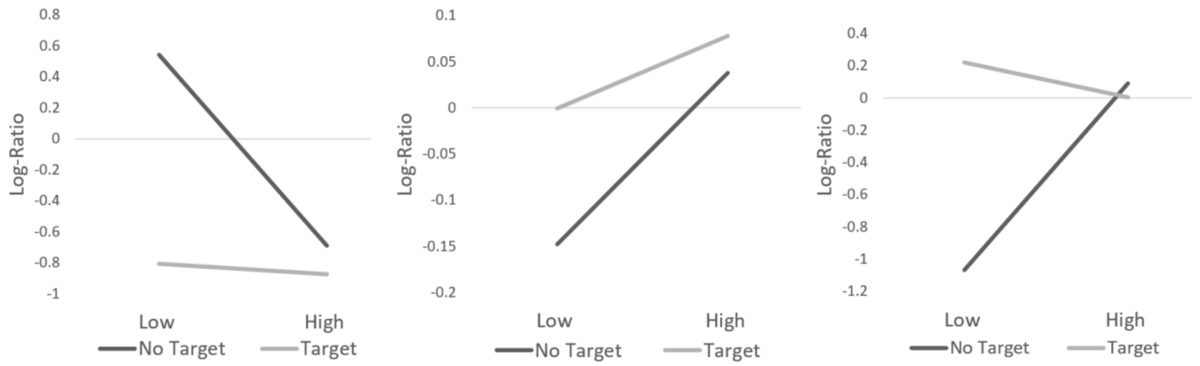

Figure 6.6: The significant interaction effects between demarcation and foot target conditions. The plots show AOI viewing ratios for Other, Final step and Penultimate step AOIs (left to right respectively).

6.5 Discussion

The present study investigated the behaviours invited by visual interventions currently used to promote safety, when pedestrians step onto a moving surface, as experienced when using an escalator (CIBSE, 2015). Specifically, the perceptual-motor adaptations invited by high contrast demarcation lines and foot targets were examined. The first hypothesis suggested that increasing the salience of visual information via high contrast lines and/or foot targets, would reduce the demands of visually extracting distal information thereby decreasing 'active search' behaviours (e.g., Thomas et al., 2021) and invite feed-forward control. Interaction effects between demarcation and target conditions indicated that salient features invited behavioural adaptations consistent with reduced attention to distal locations. These included reduced look ahead distances and later gaze transfer times from the final walkway step location for both younger and older adults (Figures 6.2 & 6.3). Because the step preceding an obstacle has been associated with adapting COM trajectory through the subsequent step (Barton et al., 2019; Matthis et al., 2017) such adaptations support an increased use of feed-forward control. Despite significant between subject effects (Table 6.3) highlighting that perturbation magnitude was greater in older than younger adults (Table 6.1), this measure was not significantly influenced by experimental conditions. Because previous research has suggested that feed-forward control is associated with reduced metabolic and cognitive demand, these results suggest that salient features enabled participants to maintain a consistent level of successful locomotion at a reduced metabolic and cognitive demand (Ellmers & Young, 2019; Matthis & Fajen, 2014).

The second hypothesis suggested that the behaviours solicited by demarcation and foot target conditions would differ, with foot targets inviting online control. Consistent with hypothesis two, the behaviour adaptations solicited by high contrast compared to low contrast demarcation lines differed to the behaviour adaptations observed between foot target and no foot target conditions (Table 6.3). In particular, foot target conditions resulted in adaptations to final step variables, including reduced step times and increased step time variability, as well as increased final step AOI viewing. Such adaptations were not identified in comparisons between high and low contrast demarcation conditions. These changes reflect the use of online control. As online control has been noted as more demanding and less stable, this result suggests that foot-targets may not invite beneficial behaviour adaptations.

Finally, the third hypothesis suggested that older adults would be less likely to be solicited by interventions that invite online control. Between subject effects identified that irrespective of experimental condition, older adults had longer and more variable approach times than younger adults. Moreover, interaction effects showed that older adults step times were less variable in conditions that included foot targets (e.g., foot targets with either high or low contrast demarcation lines) than younger adults. These findings support the third hypothesis and indicate that older adults did not utilise online control to the same extent as younger adults when foot targets were positioned on the belt surface.

6.5.1 The salience of visual information affects perceptual-motor behaviour

The primary hypothesis positioned that increasing the salience of visual information (via high contrast lines and/or adding foot targets), would reduce the demands of visually extracting distal information thereby inviting feed-forward control in both younger and older adults. Because feed-forward control is associated with maintaining locomotor performance at reduced physical demand (Barton et al., 2017; Barton et al., 2019; Chapter 5), the emergence of feed-forward control coupled with no change in perturbation magnitude between experimental conditions was expected to signify locomotor performance was maintained at lower physical demand.

In line with this hypothesis, non-significant main effects (Table 6.3) showed that perturbation magnitude for both young and old adults did not change across the experimental conditions, suggesting that, each age group maintained the same level of successful locomotion irrespective of experimental condition (Domínguez-zamora et al., 2020; Muir et al., 2015; van Andel et al., 2018). Significant interaction effects between demarcation and target conditions revealed that when younger and older participants stepped onto the moving surface with low contrast demarcation lines and without foot targets look ahead distance increased, and gaze was transferred from the walkway and belt footstep locations earlier preceding foot contact compared to all other conditions (Figures 6.2,6.3,6.4). Furthermore, AOI data analysis revealed interaction effects between demarcation and target conditions (Figure 6.6) indicating that in the no foot target low demarcation line condition: (i) all participants looked at the 'other' compared to the walkway and belt AOIs significantly more; (ii) all participants spent less time looking at the final step location; (iii) all participants spent less time viewing the penultimate step location. Comparable to the findings of Thomas and colleagues (2021), these results suggest that when visual information is more ambiguous participants increase exploratory (e.g., more distally orientated), gaze behaviours; an adaptation suggested to enhance environmental certainty prior to committing subsequent COM trajectory (Matthis et al., 2018).

Research examining gaze behaviours when overcoming locomotor challenges may help to contextualise these results. Specifically, information from approximately two step-lengths has been demonstrated as a critical threshold that constrains the adoption of feed-forward control (Barton et al., 2017; Matthis et al., 2014). However, when terrain complexity increases, participants have been found to look ahead to distal locations earlier prior to the foot contacting the ground (Barton et al., 2019; Chapman & Hollands 2007). These findings have been interpreted as gaze adaptations which ensure that walkers have enough certainty about their environment to control their body's momentum towards future footstep locations (see also: Matthis et al., 2018). Moreover, insufficient visual information prior to the two-step length threshold has been suggested to hinder a walker's capacity to utilise feed-forward control (Ellmers et al., 2019). In the current study, the interaction effects identified between demarcation and foot target conditions (Table 6.6) highlight that when stepping onto the moving surface with salient features (e.g., foot targets or high contrast demarcation lines) younger and older participants increased attention to the penultimate and final step locations, transferred gaze from these locations later and reduced look ahead distances during the approach. Such adaptations suggest that salient features enhanced environmental certainty, which in turn enabled pedestrians to attend to more proximal locations, such as the step preceding the moving surface. Incidentally, the location of the step preceding an obstacle has been identified as critical in guiding the COM trajectory during subsequent steps (Barton et al., 2017; Barton et al., 2019; Matthis et al., 2017). The increased attention given to this location further supports that salient features invited feed-forward control. Accordingly, the results infer that salient features enabled participants to maintain locomotor performance at a reduced metabolic and cognitive demand (Ellmers & Young, 2019; Matthis & Fajen, 2014).

6.5.2 Comparing the behaviours invited by demarcation and foot target interventions

Based on research establishing that perceptual-motor behaviours are relational to environmental demand (Chapter 5; Hsu et al., 2015; Swart et al., 2020), the second hypothesis proposed that compared to high contrast demarcation lines, foot targets would invite behaviours associated with online control (Barton et al., 2017; Barton et al., 2019). As online control is recognised as promoting accuracy but at increased physical demand and reduced stability (Ellmers et al., 2019; Matthis, Barton, & Fajen, 2015), it was expected that foot targets would invite less successful (e.g., more perturbed or more demanding) locomotion compared to conditions with no foot targets. The following sections compare the behaviours invited by high compared to low contrast demarcation line conditions and foot target compared to no foot target conditions, these comparisons are for both younger and older adult participants.

Demarcation lines

In contrast to research examining high contrast demarcations on staircases (Foster et al., 2014; Kim, 2009; Zietz et al., 2011), the results indicated no differences in kinematic measures between the high and low demarcation line conditions (Table 6.3). Akin to the findings of Chapter 5, this suggests adaptive behaviours are specific to environmental challenges (Chapter 5; Swart et al., 2020; Thomas et al., 2020) and may reveal a limitation in generalising interventions designed to solicit behavioural change between different environmental challenges, such as those encountered when pedestrians negotiate the sequential stepping task associated with staircases or the transition onto flat moving surfaces associated with escalator use. Although no kinematic adaptations were identified, significant main effects were identified between conditions with high or low contrast demarcation lines (irrespective of foot targets) for several gaze behaviours (Table 6.3). Compared to the low contrast demarcation line conditions, in the high contrast conditions, the look ahead distances for older and younger adults were reduced, and gaze was transferred from the walkway and belt footstep locations later. Similarly, AOI results showed that all participants viewed the ‘Other’ areas less but viewed ‘Penultimate footstep’ areas more when high contrast demarcation lines were present (Figure 6.5A). These results suggest high contrast demarcation conditions invited prioritisation of task relevant locations and reduced exploratory gaze behaviours. Congruent with the conclusion drawn regarding an increase in salient information (Hypothesis 1), these behaviours indicate the inclusion of high contrast demarcations lines invited behaviours associated with feed-forward control, which may have reduced the cognitive and physical demand of successful locomotion (Ellmers & Young, 2019; Marigold & Patla, 2007; Thomas et al., 2021).

Foot targets

Main effects between conditions with and without foot targets showed that the inclusion of foot targets invited kinematic adaptations of decreased step time, increased step time variability, and gaze adaptations of reduced look ahead distance and later gaze transfer times from the walkway and belt footstep locations. AOI results indicated that the foot targets increased the time younger and older participants spent looking at the penultimate footstep location. Consistent with conclusions drawn regarding the salience of visual information, the increased environmental certainty implied by such gaze adaptations echoes an increased use of feed-forward control. However, the increased step time variability and greater allocation of gaze towards the final step location compared to other AOIs (Figure 6.5B) suggests that foot targets also invited participants to regulate footstep position via online control (Barton et al., 2017; Matthis et al., 2017). Because online control is considered more physically and cognitively demanding than feed-forward control (Ellmers et al., 2020; Ellmers & Young, 2019; Holtzer et al., 2015; Wagshul et al., 2019), interventions that invite online control behaviours may force people closer to the limits dictated by their action boundaries (Fajen, 2005; 2007). If an individual’s cognitive or physical capacities are overloaded (e.g., the individual’s action capabilities are surpassed by the demands of controlling movement online), the risk of behavioural maladaptation increases, potentially heightening fall risk (Clark, 2015).

The adaptations solicited by foot targets may further current understanding of human predisposition towards efficient motion. Although research has established that online and feed-forward control work in synergy to overcome environmental demand (Barton et al., 2019), and that people appear to favour manipulating foot position over several steps via feed-forward control rather than alter the foot's ballistic trajectory mid-flight, limited research has considered the factors that influence behaviours associated with online control (Barton et al., 2017; Barton et al., 2019; Matthis et al., 2017; Muroi & Higuchi, 2017). The current results suggest that rather than a 'reaching strategy' where people manipulate stride length (Barton et al., 2019; Weerdesteyn et al., 2004), both younger and older adults utilised online control to temporally synchronise foot and belt target location. That is, an increase in step time variability suggests participants adapted movements to make foot contact when the target arrived at the moving footfall location. As reaching behaviours are physically demanding (Brenner & Smeets, 2003; Schillings et al., 2000) these adaptations may reflect that even when utilising online control, both older and younger adults utilised adaptations that afforded success at a reduced metabolic demand.

6.5.3 Invitations for safer behaviours in younger and older adults

Previous research has established that older adults predominantly utilise feed-forward perceptual-motor control to overcome locomotor challenges (Domínguez-zamora et al., 2020; Ellmers et al., 2020; Young & Hollands, 2010). Moreover, recent findings suggest that older individuals utilise the more efficient feed-forward control to mitigate the age related reduction in action capabilities (Chapter 5, Fajen 2007). Therefore, the final hypothesis proposed that older adults would be more resistant to invitations that would necessitate an increase in online perceptual-motor control in order to act upon them.

Comparisons between the age groups showed that older adults exhibited greater perturbation magnitude, approach times, approach time variability and viewing of the penultimate step location compared to younger adults across all conditions. Supporting the prevalent use of feed-forward control when older adults overcome environmental challenges, these adaptations suggest that older adults adapted their approach to a greater extent than younger adults when stepping onto the moving surface in all experimental conditions (Chapman & Hollands, 2007; Domínguez-zamora et al., 2020). Furthermore, an interaction effect showed that younger adults increased step time variability more than older adults in conditions that included foot targets. This interaction highlighted that the amount of adaption observed during the final step varied between the participant groups with older adults utilising mid-flight adaptations to a lesser extent. Thus, the results suggest that older adults were less drawn to invitations that solicited online control. As online control is more demanding (physically and cognitively) than feed-forward control (Ellmers et al., 2020; Ellmers & Young, 2019; Holtzer et al., 2015; Wagshul et al., 2019), the divergent behaviours of younger and older adults align with Withagen and colleagues (2012) suggestion that the physical demands of realising an affordance effect its appeal. In particular, Withagen and colleagues (2012) suggested that invitations for action depend on the relationship between the properties of the physical environment and individual (see also: Fajen 2007).

As older adults are more likely to be involved in incidents than younger adults (a finding supported through the observation that older adults exhibited greater perturbation magnitude than younger adults, irrespective of experimental condition) researchers may wish to develop interventions that invite feed-forward perceptual-motor control behaviours. Such interventions may encourage participants to regulate their approach to the moving surface, thus inviting successful locomotion whilst respecting the limits of an individual's action capabilities (e.g., Fajen, 2007). Resultantly, high contrast demarcation lines may present a method of inviting beneficial behaviour change, whereas foot targets invitations for increased online control may increase demands associated with successful locomotion when stepping onto escalator surfaces. Although this may present a viable solution, it is worth noting that this study used the same participants as Chapter 5. In Chapter 5 it was established that the older adult participants epitomised a low fall-risk group. However, because research has identified differences between high and low fall risk older adult participants (Chapman & Hollands, 2007; Ellmers et al., 2020), future research may wish to investigate the effectiveness of these interventions among high-risk older adults.

6.6 Conclusion

The present study showed that: (i) increasing the salience of visual information invites behavioural adaptations consistent with feed-forward control; (ii) although both foot targets and high contrast lines increased visual salience, the interventions invited different behaviours, with foot targets inviting behaviours associated with online control. Because online control is associated with increased cognitive and physical demand, these results suggest these interventions may force people closer to the limits imposed by action capabilities (Fajen 2007). Comparisons between age groups identified that (iii) older adults were resistant to interventions inviting online control. This finding implies the effectiveness of interventions that invite online behaviours, such as foot targets, may be limited among populations with reduced action capabilities. Future research should evaluate whether interventions that invite safer behaviours via feed-forward control offer a means of improving escalator safety.

CHAPTER 7: Inviting safer behaviours when stepping onto moving surfaces

7.1 Abstract

Previous research has identified a mutuality between people's action capabilities and their perceptual-motor behaviour adaptations. Such findings suggest that controlling concurrent movement via online control may surpass the capabilities of older adults. Consistent with this suggestion subsequent research has highlighted that older adults are resistant to interventions that invite online control. As older adults represent the 'at risk' demographic when negotiating moving surfaces, this study considers if an intervention designed to solicit feed-forward control can invite safer behaviours in older adults.

Based on research specifying the importance of the step preceding an obstacle or foot target, and findings that suggest more salient visual information invites feed-forward control; a high contrast target line was positioned at the penultimate step location. Younger (*n* = 11, 18 – 40 years, Male = 8) and older adults (*n* = 14, >60 years, Male = 5) completed ten trials in which they stepped onto a moving surface with or without an approach target. A two (age group) x two (approach condition) multilevel linear model indicated that the approach target invited perceptual-motor behaviour adaptation. In particular, increased toe distance (means of 7.8 cm and 15.7 cm for no approach target and approach target conditions respectively) reflected locomotor pointing and showed that the intervention may reduce the chance of the supporting foot overlapping the moving surface. Adaptations to walkway and belt viewing behaviours (walkway viewing reduced 11.32% and belt viewing increased 11.62% in the approach target condition) indicated the approach target provided greater availability of environmental information. Different behaviours were identified between age groups. Changes to gaze transfer times highlighted behaviours consistent with both online and feed-forward control in younger adults, whereas older adult's behaviours were consistent with increased feed-forward control. Accordingly, the target line intervention may reduce the physical demand associated with

successful locomotion, aiding the locomotor performance of adults with reduced action capabilities.

7.2 Introduction

In their seminal study published in 1982, Lee, Lishman and Thompson demonstrated that visual information was used prospectively by long-jump athletes to accurately position their foot on a long jump take-off board. Following this seminal work, a large amount of research has focused on investigating the person-environment relationship by examining human performance during locomotor pointing tasks (Barton et al., 2017). This research has established that the capacity to regulate movement using visual information is not limited to athlete populations, but is used by the general population to overcome challenges on a daily basis (Barton et al., 2017; Hayhoe & Matthis, 2018; Patla, 1996; van Andel et al., 2018b). Moreover, adapting everyday movements in order to avoid potentially harmful and energetically costly loss of balance caused by environmental challenges, requires skilful perceptual-motor control (Barton et al., 2017). In particular, adaptive locomotor research has advanced our understanding of the relationship between perception and action, with research from this field highlighting that adaptive behaviours arise from the interaction between the person and environment (Harrison et al., 2016; Warren, 1998; Withagen & van der Kamp, 2010). Reinforcing this perspective, Chapter 5 identified significant differences in the behaviours of younger and older adults as they negotiated conditions of varying complexity, such as conditions with static surfaces and no accuracy demands compared to conditions with moving surfaces and accuracy demands. Such adaptations highlighted that adaptive behaviours were a product of both an individual’s capability and the demands of the environment. For example, a significant three-way interaction effect between age group, surface condition and demarcation condition indicated that the distance between the final walkway foot-step placement and the start of the moving surface was least variable as older adults overcame the most demanding condition (moving with demarcation lines). Although numerous studies have explored the behaviours of different populations as they overcome environmental challenges (e.g., Chapman & Hollands 2006; Ellmers et al., 2020; Chapter 5), the capacity of environmental design to invite specific, safer, action has received less attention (Chapter 6; Thomas et al., 2021; Withagen et al., 2016; Zietz et al., 2011).

Evidence in the locomotor literature indicates that the initial evidence of prospective control reported by Lee and colleagues (1982), can be further expanded to encompass online and feed-forward perceptual-motor control (Barton, Matthis, & Fajen, 2017). Online control reflects adaptations to concurrent movements following perturbation or inaccuracy. Such adaptations are considered physically and cognitively demanding, and have been described as 'mid-flight corrections' (Barton et al., 2017; Reynolds & Day, 2005; Weerdesteyn et al., 2004). Feed-forward control reflects adaptations made during the steps preceding a potential perturbation (e.g., obstacle or foot target). Because feed-forward adaptations occur in advance, researchers have proposed that the availability of visual information pertaining to the approaching constraint invites people to exploit the mechanical forces inherent to bipedal locomotion (Higuchi, 2013). Such behaviours are therefore considered to promote locomotor stability and energetic efficiency while overcoming environmental challenges (Matthis & Fajen, 2013; 2014).

Research has suggested online and feed-forward control work synergistically to promote successful locomotion (Matthis et al., 2017). For example, Muroi and Higuchi (2017) examined locomotor performance as participants traversed a 3m walkway and negotiated an aperture whilst holding a horizontal bar. Their experiment compared four conditions which manipulated the availability of visual information. Specifically, visual information was (i) not occluded; (ii) occluded after 1.5s static viewing; (iii) occluded after taking two steps and then stopping; (iv) occluded after taking two steps but not stopping. Findings showed that when vision was occluded after two steps in conditions iii and iv, aperture collisions increased. Furthermore, fundamental movement patterns (such as where to walk, how to rotate the body, and when to stop walking) were maintained but maladaptive behaviours, such as earlier body rotation (relative to distance from the aperture) and reduced movement speed, emerged. These findings suggest feed-forward control established a broad level of success, but visual occlusion negative impacted upon the ability of participants to fine-tune movements using online control. Such findings highlight that the broad level of accurate movement contributed by feed-forward control subsequently reduce the demand of online control to fine-tune movement (see also: Barton et al., 2017; Zhao & Warren, 2017). Consistent with this interpretation, research manipulating the availability of distal visual information during complex terrain walking has showed that obstacle collision was more frequent and walking speed was reduced when look ahead distances were limited to less than two step lengths (Matthis & Fajen, 2014). The authors concluded that visual information from distances of greater than two step lengths enabled walkers to exploit feed-forward control to manipulate the passive mechanical forces inherent to bipedal locomotion, thereby avoiding obstacles with increased stability and at reduced energetic demand (Barton et al., 2019; Higuchi, 2013).

Research manipulating the availability of visual information has also shown that when the prominence of distal environmental information is increased (e.g., by including high contrast demarcation lines), perceptual-motor adaptations reflect feed-forward control (Chapter 6; Thomas et al., 2021; Zietz et al., 2011). In these studies, locomotor performance has been shown to improve when the visual salience of future targets/obstacles is increased. For example, participants have been noted as being better able to avoid contact with obstacles (Rietdyk et al., 2011) and exhibit behaviours associated with greater stability (Zietz et al., 2011) in more salient conditions. However, when negotiating environments that require increased movement accuracy, such as foot targets (Chapter 6), or environments that limit opportunities for stepping, such as rough mountain paths (Matthis et al., 2018), online control behaviours have been identified. Put simply, these works highlight that feed-forward control can be considered as promoting stability and providing a broad level of accuracy at reduced metabolic demand, while online control has been recognised as more physically demanding and less stable, but more accurate.

Building on these works, adaptive locomotor research has suggested the synergy between control modes allows walkers to overcome environmental challenges with efficiency, stability, and precision (Matthis, Barton, & Fajen, 2017). For example, although people are capable of using online control to fine-tune their foot's trajectory mid-flight (e.g., Weerdesteyn et al., 2004), a preference to not exclusively manipulate the body's concurrent motion has been identified (Barton et al., 2019). In fact, research pertaining to accurate foot placement during walking has highlighted that opposed to continuous feedback-driven muscular adaptation (i.e., online control), pedestrians prefer to make adaptations during the steps preceding obstacles or foot targets (Higuchi, 2013; Matthis, Barton, & Fajen, 2017; Moraes, Lewis, & Patla, 2004). Research undertaken using locomotor-pointing paradigms has established that adaptations to footstep location and push-off force magnitude from the supporting limb allows people to manipulate the trajectory of their centre of mass (COM) throughout the subsequent step, thus efficiently influencing subsequent foot placement at reduced physical demand (Barton et al., 2017; Matthis, et al., 2017). Consistent with this conclusion, Chapter 5 examined how people step onto moving (compared to static) surfaces and revealed that both younger and older participants prioritised the penultimate step location[14], as evidenced by later gaze transfer away from, and increased viewing time on the step location that preceded stepping onto a moving surface. Moreover, when accuracy was demanded by demarcation lines both younger and older

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[14] Penultimate step location refers to the final step on the walkway surface prior to transitioning onto the moving surface.

adults demonstrated reduced toe distance variability. These adaptations indicated that both younger and older participants more actively regulated foot placement of the penultimate step, and therefore influenced their subsequent ballistic COM trajectory when increased accuracy or stability was demanded (see also: Chapter 5; Matthis et al., 2015; Timmis & Buckley, 2012).

The placement of the penultimate step has important considerations regarding the task of stepping onto a moving surface. In a study exploring the causes of escalator incidents, Beards and colleagues (2022) found that falls predominantly occurred in older adults who lost their footing when getting onto the escalator. Supporting Beards findings, the distance between the supporting limb and the moving surface (i.e., toe distance) has been found to be reduced when participants step onto moving (compared to static) surfaces and between conditions that called for increased accuracy (Chapter 5). Moreover, findings in both Chapters 5 and 6 highlighted that older adults toe distance between the end of the walkway and the moving surface was less than younger adults in all experimental conditions. Although significant between subject effects were not identified (*p*= .106 & *p*= .057; Chapters 5 and 6 respectively), this pattern of behaviour is meaningful as a reduction in toe distance between the end of the walkway and the moving surface may increase the risk of overlapping the transition between the walkway and the escalator surface; a miss-step, which could potentially perturb the supporting limb and lead to a loss of footing. Based on these findings it is beneficial to assess if interventions that invite participants to control their movements using feed-forward control (e.g., Chapter 6; Skervin et al., 2021; Thomas et al., 2021; Zietz et al., 2011), as well as increase toe distance between the end of the walkway and the moving surface could bring about safer locomotion when stepping onto a moving surface, particularly in older adults.

7.2.1 Action capabilities and perceptual-motor control

Although a synergistic relationship between control modes has been demonstrated, the different demands associated with online and feed-forward control has been shown to influence how pedestrians overcome locomotor challenges (Chapters 5 and 6). In particular, research has shown that an individual's action capabilities act as a boundary on perceptual-motor control adaptations (Fajen, 2005). Based on the well documented decline in physical and cognitive capacity associated with advancing age (Mazaheri et al., 2014; van Andel et al., 2018b) and the increased frequency and severity of falling in older adults (Galna et al., 2009; Kovacs, 2005; Schminke et al., 2013), a multitude of research has compared the adaptive behaviours of younger and older participants. Such research has commonly reported different perceptual-motor behaviours between the age groups. For example, Chapman and Hollands (2006) showed that high fall risk older adults looked away from proximal targets significantly earlier than younger adults when required to position their foot onto a target. Based on these results, the authors suggested that older participants prioritised adapting behaviours to overcome distal constraints over the accuracy of concurrent movements (see also: Young, Wing, & Hollands, 2012). Drawing on affordance-based control (Fajen, 2007), the different behaviours observed between age groups reflects that individuals are sensitive to the limits of their action capabilities (Chapter 5). Furthermore, research considering the age associated physical and cognitive decline alongside reports of feed-forward motor control being less physically and cognitively demanding compared to online control indicates that the prevalent use of feed-forward control in older adults may be due to the increased demands of online control surpassing the limits dictated by their action capabilities (Chapters 5 and 6; Fajen 2007; Withagen et al., 2012).

7.2.2 Inviting safer behaviours

Recent developments within ecological psychology suggest that affordances are not mere possibilities for action but can be considered invitations for specific behaviours

(Bruineberg & Rietveld, 2014; Rietveld & Kiverstein, 2014; Withagen et al., 2012, 2017). Similarly, literature considering public health interventions suggests environmental design can invite specific behaviours (Skervin et al., 2021; Thomas et al., 2021; Withagen & Caljouw, 2016; Zietz et al., 2011) and has even been suggested as a consideration that may improve safety on escalator surfaces (Beards et al., 2022). Therefore, after exploring the behaviours underpinning successful locomotion in moving surface environments (Chapter 5), subsequent research evaluated if environmental design could invite safer behaviours (Chapter 6). Specifically, based on currently applied interventions, Chapter 6 evaluated how salient visual features, such as high or low contrast demarcations and foot targets, influenced younger and older adults' behaviours. Regardless of age group, when no salient features were presented on the moving surface, look ahead distances were increased, and the penultimate step viewing was reduced as participants approached the moving surface (see also: Thomas et al., 2021). These findings suggest that increased visual salience made it easier for participants to gather environmental information and enhanced certainty (Matthis et al., 2018). As distal information was available and acted on prior to stepping onto the moving surface, these results suggest that salient features invited behaviour adaptations consistent with increased feed-forward control. This finding not only affirmed environmental design can invite specific (safer) behaviours (Caljouw et al., 2019; Thomas et al., 2021; Withagen & Caljouw, 2016), but indicate design interventions influence how people control their movements.

Although previous research has suggested that salient features invite behaviours consistent with feed-forward control, adaptive behaviours have been shown to differ between participants groupings (e.g., age) and intervention type (Thomas et al., 2021; Zietz et al., 2011). Consistent with the premise outlined by affordance based control, which specifies that people's behaviours are relational to the interaction between their action capabilities and environmental demands (Fajen 2007), Chapter 6 found behaviours differed between younger and older adults and between demarcation line and foot target interventions. Specifically, conditions with foot targets (e.g., foot targets with high contrast demarcation lines and foot targets with low contrast demarcation lines) invited adaptations such as more variable step times and greater visual attention allocated to the final step location (e.g., the placement of the footstep onto the moving surface). These changes evidenced that adaptations occurred during the step onto the moving surface, which indicated that foot targets invited behaviours associated with online control. Furthermore, an interaction effect between age and target condition highlighted that older adults did not adapt concurrent movement to the same extent as younger adults. Aligning with contemporary accounts of agency (Withagen et al., 2012, 2017), which propose that behaviour emerges from the interplay between the environment's invitations and the individual's capacity to modulate the extent they are attracted, or resistant to affordances invitation (see also: Kiverstein, van Dijk, & Rietveld, 2019), Chapter 6 suggested that older adults reduced action capabilities led to this age group being resistant to invitations that solicited behaviours associated with the more demanding online control. As older adults represent the at-risk demographic when stepping onto escalators (Beards et al., 2022; Schminke et al., 2013), the effectiveness of interventions that invite online adaptation to overcome the challenges of the moving surfaces may be limited. Consequently, design interventions that invite feed-forward behaviours may have the potential to invite successful locomotion at a reduced physical and cognitive demand.

As previously alluded, the location of the supporting foot (the penultimate step) is not only key to guiding the COM trajectory throughout the subsequent step via feed-forward control (Barton et al., 2017; Matthis, et al., 2017), but based on the association between loss of footing and falls observed as older escalator users step onto the moving surface (Beards et al., 2022), may play a direct role in escalator safety. As Chapter 6 presented evidence that foot targets invited locomotor pointing behaviours, the use of a similar, target based, intervention positioned on the approach to the moving surface may invite participants to regulate their penultimate step location, thus both aiding the regulation of the penultimate step and inviting feed-forward control, whilst inviting greater toe distances and reducing the risk of participants undermining the supporting limb (Beards et al., 2022).

7.2.3 The current study

This chapter aimed to evaluate whether salient visual features added to the penultimate footstep location would invite beneficial behaviour adaptation. The primary hypothesis suggested that the addition of a high contrast target line positioned on the walkway will invite participants to regulate their penultimate footstep location. Such an adaptation would reduce both task demand by inviting feed-forward control and the chance of miss-stepping by increasing toe distance (the distance between the supporting limb and the moving surface) measures. Confirming the adoption of feed-forward behaviours, it was expected that gaze adaptations such as earlier gaze transfer away from the penultimate step location as well as increased look ahead distances or viewing of the belt, rather than walkway areas of interest (AOI's) would be observed in the approach target condition.

Because of the age related differences in action capabilities, the second hypothesis positioned that the behaviours of younger and older adults would differ. Building on the results of Chapter 6, which highlighted the emergence of online control when foot targets were presented to younger adults, it was expected that younger adults would use online control to position their foot on the approach target line whereas older adults would not. It was expected that online control would be evidenced by behaviours such as later gaze transfer time away from this foot-step location and increased variability throughout concurrent movement, as exemplified by increased step time and step length variability.

7.3 Method

7.3.1 Participants

Power analysis, conducted using G*Power (Faul et al., 2007), outlined that based on toe distances between the end of the walkway and moving surface reported when participants stepped onto moving surfaces with high contrast demarcation lines during Chapter 6, a minimum of 5 participants per group would be required to obtain 80% power (Cohen, 1988). The participants (N = 25) were grouped based on age boundaries used in previous research (Alcock et al., 2013; McCrum et al., 2017; Schminke et al., 2013). Younger adults (18 – 40 years, M = 26.5 SD = 5.7 years, *n* = 11, Male = 8) and older adults (60 years and older, M = 71.5 SD = 6.9 years SD = 5.7 years *n* =14, Male = 5) were recruited from the university and local community. As a manipulation check between the participant groups a questionnaire battery was administered as per Chapters 5 and 6. Ethical approval was granted at an institutional level with all participants providing signed consent and established no history of falling or physiological and neurological impairment.

7.3.2 Apparatus

The apparatus used to collect kinematic and gaze behaviours was as described in Chapters 5 and 6. Participants requiring the use of eye-glasses for daily locomotor activities (n=7, old=6) excluded due to incompatibility with the gaze tracking equipment.

7.3.3 Procedure

The experimental protocol was identical for all participants, and identical to Chapters 5 and 6 regarding approach walkway dimensions and belt characteristics. In this chapter, two conditions were tested (Figure 7.1), with ten trials completed in each condition. The order of conditions was counterbalanced per participant, in the ‘no approach target’ condition, no line was added to the walkway, whereas in the ‘approach target’ condition, a 10cm wide black target line was added 12cm away from the end of the walkway (Figure 7.1). The distance of 12cm was based on the mean distance between the toe of the standing foot and the transition between the end of the walkway and the belt surface as participants negotiated less challenging conditions in chapter 5. Specially, the distance was selected based on toe distances recorded for older adults when stepping onto a stationary belt surface without accuracy demands and younger adults when stepping onto moving surfaces without accuracy demands (Chapter 5). In both conditions participants were instructed to step onto the moving surface while avoiding the high contrast demarcation lines. No further instruction was given to participants. A minimum 30-point light reflectance value difference must be present to represent ‘high’ contrast (British Standards Institution, 2018). As per Chapter 6, the mean of five spot luminance measures (Minolta SL110 Luminance meter) identified light reflective values (LRV) of 2.86 (walkway surface) and 62.86 (Black target line). The 60.0 difference between measures established contrast between demarcation line and the surface was sufficient to allow classification as high contrast as per British standards (BS 8300:2009). Participants received no instruction pertaining to the targeting line. No failure to complete the task was observed.

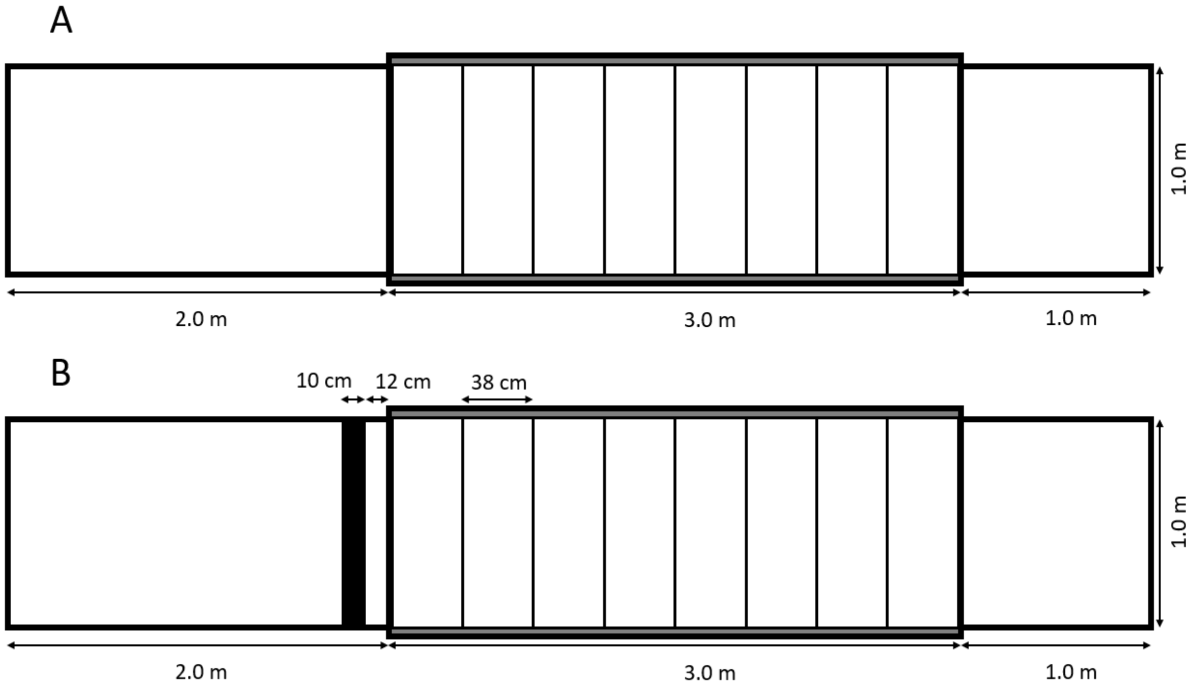

Figure 7.1: Top view of experimental task set up and dimensions. A shows no approach target condition; B shows approach target condition.

7.3.4 Measures

Kinematic dependent variables

Kinematic measurements were taken as per Chapter 5 and 6.

Gaze dependent variables

Gaze measurements were taken as per Chapter 5 and 6.

7.3.5 Statistical Analysis

Self-reported measures

Self-reported measurements were taken as per Chapter 5 and 6.

Perceptual-motor measures

A multilevel linear model examined perceptual-motor (kinematic and gaze) behaviours (Hoffman & Rovine, 2007). The analysis consisted of a 2 (Age-group [young adults, old adults]) x 2 (Approach target [No-Targets, Targets]) design, with approach target as the within subject factor and age group as the between subject factor. As per the procedure outlined by Field and colleagues (2012), analysis was undertaken in r (RStudio Team, 2020) using the 'nlme' (Pinheiro, Bates, DebRoy, Sarkar, & R Core Team, 2020), 'ggplot2' (Wickham, 2016), and 'pastecs' (Ibanez & Grosjean, 2018) packages. Where data were non-normally distributed, significant effects were cross checked with robust ANOVAs based on trimmed means (Field et al., 2012; Mair & Wilcox, 2020; Thomas et al., 2021).

Area of interest analysis

Compositional analysis was undertaken as described in Chapters 5 and 6. However, in this study, repeated measures multivariate analysis of variance (MANOVA) was applied to ILR-transformed data to determine the separate main effects of age and approach conditions. To interpret significant effects, geometric mean bar plots were constructed using log-ratios (see: Gupta et al., 2018).

7.4 Results

7.4.1 Self-reported measures

Mann-Whitney U tests identified significant differences between age groups in the falls efficacy scale. No other significant differences were found between age groups (Table 7.1). Bayes factors also indicated positive evidence (Raftery 1995) for differences between age groups in measures of falls efficacy.

Table 7.1: Characteristics of younger and older adults

	Younger		Older				
	Mean	SD	Mean	SD	*U*	*p*	*BF*$_{10}$
Fall Efficacy Scale (international)	17.4	0.51	18.6	1.60	39.5	0.034 [a]	3.314
Activities Balance Confidence Scale	96.40	2.21	94.50	4.01	61.0	0.396	0.759
MSRS Total	23.5	10.44	20.71	9.24	66.0	0.564	0.447
CMP	12.5	6.20	13.00	7.26	77.0	1.000	0.374
MSC	11.0	6.00	7.71	2.89	47.0	0.102	1.171

[a] Significant difference (p < .05) between age groups

Table 7.2: Age group and experimental condition comparisons for approach variables (Mean ± SD)

	No Target	Approach Target
Perturbation Magnitude (cm) [c]		
Younger	9.7 ± 0.7	9.0 ± 0.9
Older	8.4 ± 0.8	9.1 ± 0.6
Toe Distance Variability (cm)		
Younger	4.7 ± 3.8	3.5 ± 1.9
Older	2.7 ± 1.2	3.2 ± 1.9
Approach Time (s) [a ,b]		
Younger	2.05 ± 0.28	2.08 ± 0.27
Older	2.23 ± 0.25	2.38 ± 0.25
Approach Time Variability (s)		
Younger	0.16 ± 0.07	0.16 ± 0.08
Older	0.17 ± 0.07	0.19 ± 0.04
Look Ahead Distance (m)		
Younger	1.98 ± 0.71	2.45 ± 1.62
Older	2.14 ± 0.81	2.92 ± 2.39

[a] Significant difference (*p*<.05) between target conditions

[b] Significant differences between age groups

[c] Significant interaction effect between condition and age group

Table 7.3: Age group and experimental condition comparisons for final step variables (Mean ± SD)

	No Target	Approach Target
Step Length (cm) [a]		
Younger	67.6 ± 8.7	70.5 ± 7.3
Older	61.2 ± 6.3	67.2 ± 8.6
Step Length Variability (cm) [a]		
Younger	10.9 ± 2.7	7.6 ± 2.4
Older	9.0 ± 2.2	7.1 ± 1.7
Step Time (s) [a]		
Younger	0.60 ± 0.11	0.63 ± 0.12
Older	0.53 ± 0.12	0.63 ± 0.14
Step Time Variability (s)		
Younger	0.11 ± 0.06	0.18 ± 0.07
Older	0.12 ± 0.09	0.19 ± 0.05
Belt Gaze Transfer (ms)		
Younger	1024 ± 369	835 ± 476
Older	1089 ± 720	680 ± 483

[a] Significant difference (*p*<.05) between target conditions.

Table 7.4: Statistics for approach and final step variables

		Approach Condition		Age Group		Interaction	
	DF	$\chi 2$	*p*	$\chi 2$	*p*	$\chi 2$	*p*
Perturbation Magnitude	1	0.120	0.729	1.167	0.280	4.122	0.042 [a]
Step Length	1	8.704	0.003 [a]	3.110	0.078	1.232	0.267
Step Length Variability	1	14.044	<0.001 [a]	3.540	0.060	1.174	0.278
Step Time	1	9.042	0.003 [a]	0.391	0.532	3.021	0.082
Step Time Variability	1	0.823	0.364	1.415	0.234	0.413	0.520
Toe Distance	1	24.421	<0.001 [a]	0.306	0.580	4.335	0.037 [a]
Toe Distance Variability	1	0.172	0.678	2.558	0.110	2.051	0.152
Approach Time	1	4.561	0.033 [a]	5.987	0.014 [a]	2.391	0.122
Approach Time Variability	1	0.497	0.481	0.928	0.335	0.210	0.647
Look Ahead Distance	1	2.099	0.147	2.519	0.112	1.136	0.286
Walkway Gaze Transfer	1	0.296	0.586	0.739	0.390	6.734	0.009 [a]
Belt Gaze Transfer	1	0.282	0.595	0.062	0.586	2.996	0.083

[a] Significant difference (*p*<0.05) between conditions

7.4.2 Approach variables

Perturbation Magnitude No significant main effects were identified between surface approach target conditions, or between age groups (*p*>.05, Table 7.2). A significant interaction effect was identified between age group and approach condition (*p*=.042). This result showed that older adults perturbation magnitude increased when a foot target was included, whereas younger adults was reduced.

Approach Time Significant main effects (Table 7.2) were identified between approach target conditions (*p*=.033) and between age groups (*p*=.014). These results show that approach time was increased when participants stepped onto the moving surface with an approach line in place and was greater for older adults. No significant interaction effect was identified (*p*>.05, Table 7.4).

Approach Time Variability No significant main or interaction effects (all *p*>.05, Table 7.4) were found.

Toe Distance A significant main effect (Table 7.2) was identified between approach target conditions (*p*< .001). This result showed that toe distance was significantly increased when the approach target line was in place (Figure 7.2). There was also a significant interaction effect between age group and approach line condition (*p*=.037; Table 7.4). This result showed that in the approach target condition older adults increased their toe distance more than younger adults.

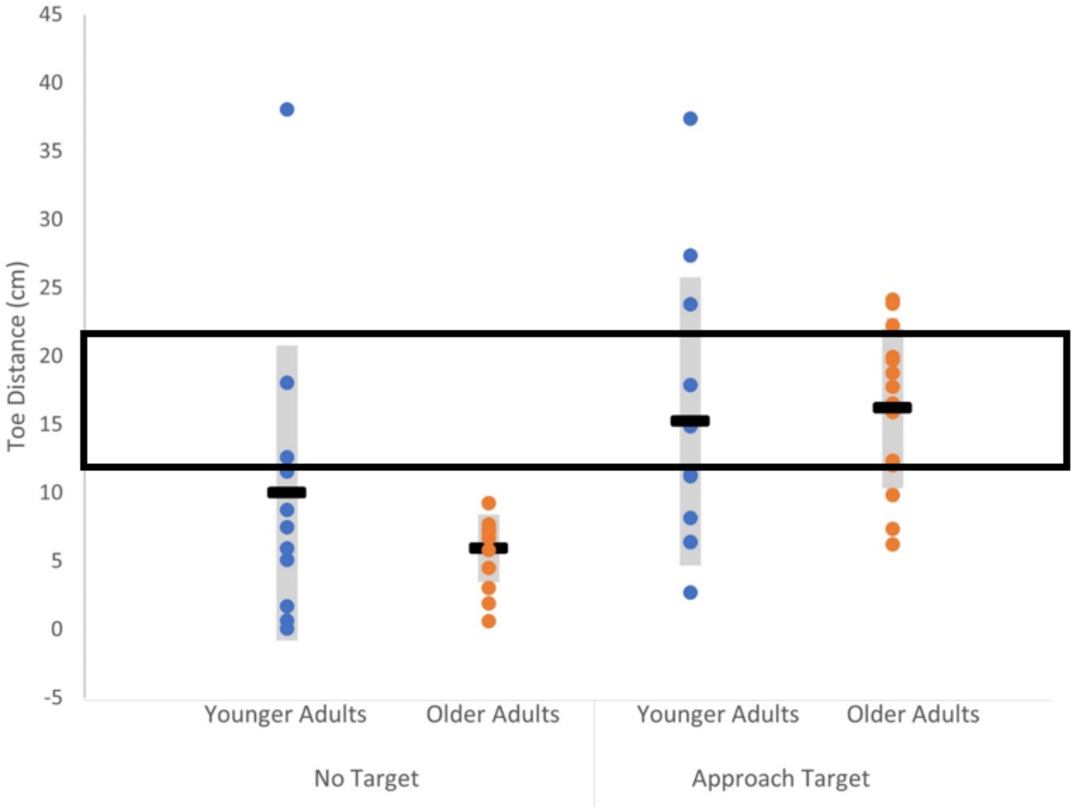

Figure 7.2: Toe distances of younger and older adults in both experimental conditions. Significant main effects (*p*<.05) highlighted that toe distances, as measured between the supporting limb and the moving surface, were significantly different between age groups. Moreover, a significant interaction effect (*p*<.05) indicated older adults increased toe distance by a greater amount in the approach target condition compared to younger adults. The black box signifies location of approach marker.

Toe Distance variability No significant main or interaction effects (all *p*>.05, Table 7.4) were found.

Look Ahead Distance No significant main or interaction effects (all *p*>.05, Table 7.4) were found.

Walkway Gaze Transfer A significant interaction effect was identified (Table 7.2). The interaction effect showed that older adults looked away from the walkway step location earlier in the target line condition, whereas younger adults looked away later (*p*=.009)

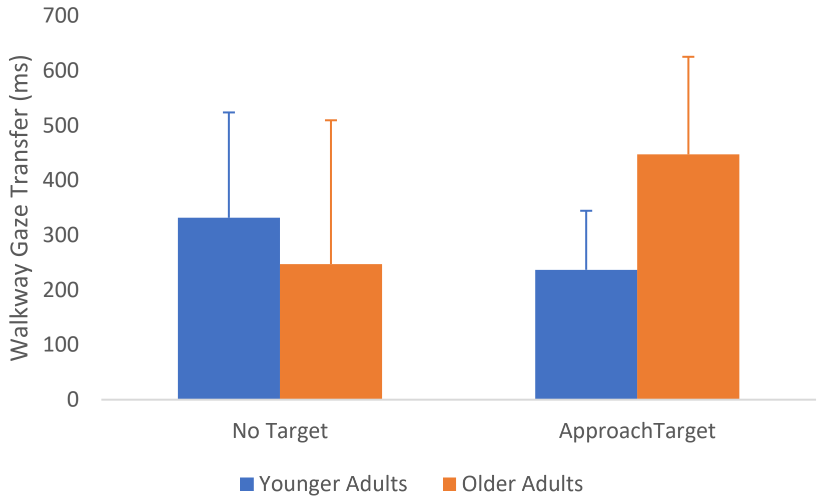

Figure 7.3: Walkway gaze transfer times between age group and experimental conditions. Plot shows that older adults looked away earlier in the target line condition whereas younger adults looked away later.

7.4.3 Final Step Variables

Step Length Significant main effects (Table 7.3) were identified between approach conditions. Specifically, step length increased when participants stepped onto the moving surface in the approach line condition (*p*=.003). There was no significant between subject or interaction effects (all *p*>.05, Table 7.4).

Step length variability A significant main effect (Table 7.3) was identified between approach conditions (*p*< .001). This main effect evidenced that step length was less variable when stepping onto moving surfaces in the approach line condition. There was no significant between subject or interaction effects (all *p*>.05, Table 7.4).

Step Time a Significant main effect (Table 7.3) was identified between approach conditions.

This main effect showed that step time was increased when participants were in the approach line condition. There was no significant between subject or interaction effects (all *p*>.05, Table 7.4).

Step Time Variability No significant main or interaction effects (all *p*>.05, Table 7.4) were found.

Belt Gaze Transfer No significant main or interaction effects (all *p*>.05, Table 7.4) were found.

7.4.4 AOI Analysis Results.

A repeated measures MANOVA identified main effects between approach conditions for isometric log ratio of belt and walkway viewing (F(1,15) 10.820, *p* =.005, η^2 =.419). Put simply, the approach target increased the time spent looking at the belt and reduced the time spent looking at the walkway. No other significant effects were identified.

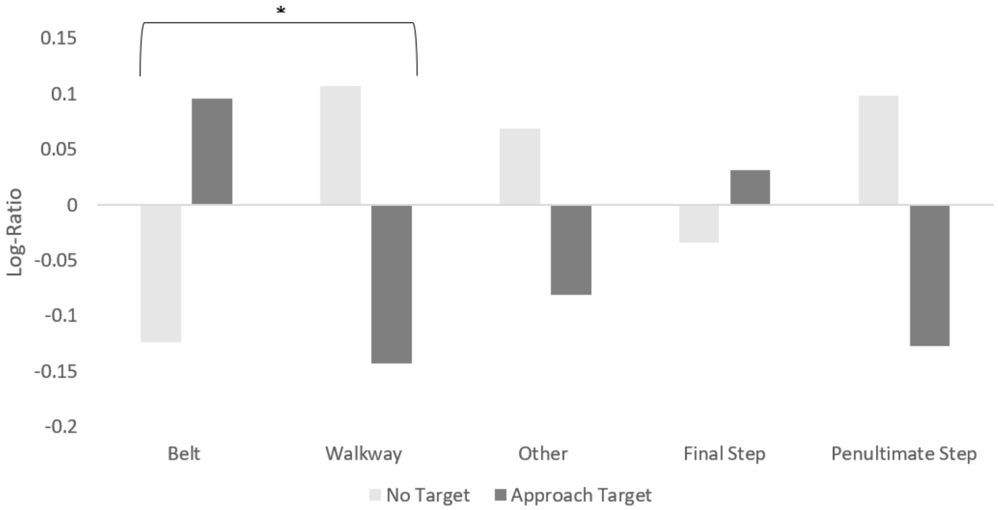

Figure 7.4: Area of interest viewing ratios for approach conditions. The graph presents the geometric mean of each expressed in terms of a ratio of the geometric mean, measured on a logarithmic scale. A ratio of 0 reflects each group is equal, positive, or negative values show the geometric mean is larger or smaller respectively than the population mean. Asterix (*) denotes significant main effects (*p*<.05) between belt and walkway isometric log ratios. The actual ratio of the geometric group mean to the whole group geometric mean can be calculated by taking the exp of the value from 100.

7.5 Discussion

The aim of this experiment was to evaluate the behaviours solicited by a high contrast target line positioned on the approach to a moving surface. The primary hypothesis proposed that the approach line would reduce the demands of successful locomotion by inviting feed-forward control as well as reduce the risk of miss-stepping by increasing toe distance between the standing foot and the edge of walkway and moving surface. In line with this hypothesis, results revealed that when stepping onto moving surfaces with an approach marker, both younger and older adults increased step length, toe distance, step time and approach time as well as reduced step length variability. Moreover, all participants also increased the time spent looking at the belt, compared to the walkway AOI in the approach marker condition (Figure 7.4). These results support research suggesting that environmental design can invite specific, safer, behaviour adaptations (Caljouw, De Vries, & Withagen, 2017; Chapter 6; Desmet & Hekkert, 2007, 2009; Thaler & Sunstein, 2009).

Self-reported measures (Table 7.1) identified that older adult participants exhibited increase fall efficacy scores than younger adults, an adaptation previously associated with fear of falling (de Melker Worms et al., 2017; Maria et al., 2016). This difference affirmed that the older adult participants epitomised a low fall risk group (Chapters 5 and 6). Because of the different action capabilities acknowledged between age groups (Fajen, 2007; Maidan et al., 2018; van Andel et al., 2018b) and previous findings highlighting that older adults were resistant to invitations for online control (Chapter 6), the second hypothesis suggested that younger adults greater action capabilities would lead to behaviours associated with online control. Consistent with the second hypothesis, between subject effects identified that approach times were greater in older adults regardless of approach condition. Several interaction effects were noted between age and approach conditions (Table 7.4). These interaction effects showed that when the approach target was included: (i) perturbation magnitude was increased in older adults but decreased in younger adults; (ii) toe distance increased by a greater amount from the edge of the walkway and moving surface for older adults; (iii) gaze was transferred from the penultimate step location earlier in older adults, but later in younger adults (Figure 7.3). These findings suggest that the approach line may have invited behaviours associated with feed-forward control in older adults, whereas behaviours associated with online control were also observed in younger adults.

7.5.1 Inviting safer behaviours

In line with the first hypothesis, kinematic adaptations recorded in the approach marker condition offered support for increased feed-forward control. In particular, a reduction in step length variability was recorded for older and younger adults as they transitioned onto the moving surface. As online control has been associated with increased movement variability during the final step (Matthis et al., 2017), such adaptation suggests that participants were less dependent on adapting concurrent movement (e.g., participants adhered more closely to ballistic trajectory) to establish the footstep location on the moving surface. Further evidence for increased feed-forward control can be established from older and younger adult gaze behaviours. Gaze adaptations show the approach line invited participants to increase viewing of distal (belt) locations and reduce viewing of proximal (walkway) locations (Figure 7.4). Such adaptations suggest that when the approach marker was applied participants increased attention to distal stepping constraints (Thomas et al., 2021).

Research exploring how visual factors influence perceptual-motor behaviours has established that conditions with low visual salience invite increased viewing as participants more actively searched for environmental information (Chapter 6; Thomas et al., 2021). As the belt's visual characteristics did not change in the current study, gaze behaviour adaptations suggest the approach line increased certainty regarding proximal locations, in turn inviting participants to allocate visual attention to distal areas. Supporting this conclusion, research exploring gaze behaviours during sequential locomotor pointing tasks has reported that participants attended to more proximal areas when challenged or fearful of falling, an adaptation associated with increased online control (Domínguez-Zamora & Marigold, 2019; Ellmers, Cocks, & Young, 2020; Ellmers & Young, 2019; Matthis & Fajen, 2014; Matthis et al., 2018). Together, the changes in gaze behaviour measured between experimental conditions indicate that participants had enough certainty about the penultimate step location to commit their body's momentum towards this footstep location while increasing the time spent visually exploring distal stepping constraints, which are both behavioural adaptations associated with feed-forward control (Ellmers et al., 2019; Matthis et al., 2014; Young et al., 2012).

Aside from inviting feed-forward control, a significant increase in toe distance between the standing foot and the edge of the walkway and moving surface was identified in the approach target condition. This change highlights that all participants increased the distance between their supporting limb and the start of the moving surface and suggest participants positioned their foot on the target line (Table 7.2; Figure 7.2). Moreover, the non-significant differences identified between toe distance variability measures (p>.05, Table 7.4) suggests that the consistency in foot placement (i.e., accuracy) was not different between conditions. As toe distance has been identified as potentially associated with escalator incidents (Chapter 5), these findings suggest that the approach target line invited safer stepping behaviours in both younger and older participants.

7.5.2 Inviting behaviours in older and younger adults

Consistent with hypothesis two, the adaptations invited by the approach line differed between younger and older adult participants. Significant interaction effects (Table 7.4) indicated that the approach line: (i) increased perturbation magnitude in older adults but decreased perturbation magnitude in younger adults; (ii) increased older adults toe distance by a greater amount than younger adults (Figure 7.2); and (iii) invited earlier gaze transfer from the penultimate step location in older adults, but later gaze transfer from the penultimate step location in younger adults (Figure 7.3). Together these findings indicate that, unlike their younger counterparts, older adults were resistant to invitations soliciting online control.

The increase in perturbation magnitude for older adults suggests that the approach marker invited deviation from a ‘smooth’ approach. Although successful locomotion has been characterised by a person’s ability to overcome environmental challenges and reduce the environments impact to locomotion (Donelan, 2016), the greater deviation from a smooth approach recorded in older participants may be a result of greater attention to regulating the step onto the moving surface during the approach. Supporting this suggestion, older adults exhibited earlier walkway gaze transfer times in the target line condition (Table 7.2, Figure 7.3). Moreover, contrasting adaptations observed in younger adults (e.g., reduced perturbation magnitude and later gaze transfer times) indicate that the approach target line may have invited younger adults to use online control to step onto the target line before transitioning onto the moving surface, resulting in a ‘smoother’ less perturbed approach phase for this age group.

Research examining the perceptual-motor behaviours of younger, older low fall risk and older high fall risk adults completing a sequential targeted walking task has reported that high risk older adults looked away from proximal step locations earlier than both low risk older and younger adults, an adaptation that was associated with increased anterior-posterior (A-P) foot placement variability (Chapman & Hollands, 2006). The authors suggested such behavioural adaptations evidenced that older adults prioritised future movements (e.g., feed-forward control) over the accurate execution of concurrent movement (e.g., online control). Despite the earlier gaze transfer for older adults, the current results from the current Chapter did not result in an increase in the variability of the distance measured between the supporting limb and the moving surface (i.e., toe distance variability) - comparable with increased anterior-posterior foot placement variability in the study of Chapman and Hollands (2006) - between the age groups or experimental conditions, indicating the approach marker did not solicit the loss of accuracy previously associated with earlier gaze transfer times (Chapman & Hollands, 2006; Ellmers et al., 2019; Young et al., 2012).

In a later study, Chapman and Hollands (2007) found earlier gaze transfer times from proximal step locations but no significant difference in A-P foot placement variability between low and high fall risk older adults (Chapman & Hollands 2007). Such results echo the current study's findings (Table 7.4), which may suggest that the older participants in this study epitomised a low risk group. Such a suggestion is supported by the increased fall efficacy scores found in the older adult age group (Table 7.1). Moreover, regardless of fall risk classification, the use of feed-forward control has been associated with promoting stability and energetic efficiency while overcoming environmental challenges (Matthis & Fajen, 2013; 2014). Accordingly, these results allude to older participants in the current study finding the task of stepping onto a moving surface less demanding when the approach target was in place.

Overall, these finding have practical implications that suggest that a target line positioned at the penultimate step location may offer a method of improving escalator safety. However, Beards and colleagues (2022) highlighted different incident rates between users of ascending and descending escalators, which reflect behaviours may be influenced by direction of travel, a factor which was outside of the scope of this study. As such future research should therefore aim to evaluate the application of an approach target line via a field based experimental design. Such an approach is advocated in order to consider if this intervention may present a method of promoting successful location in everyday settings. Furthermore, as the older participants in this study represented a low fall risk group, further research may wish to evaluate the behaviours invited by the approach target line intervention in high fall risk older adults.

7.6 Conclusion

In conclusion, the present study found that applying a high contrast approach target line invited adapted behaviours in all participants. Although these behaviour adaptations were generally consistent with an increased use of feed-forward control, younger adult participants also adapted behaviours via online control. Consistent with the results of Chapter 5, older adults, who are recognised as the ‘at risk’ demographic when stepping onto moving surfaces, were resistant to invitations to online control. Overall, these results indicate that the inclusion of a high contrast approach line may reduce the demands of stepping onto a moving surface for older adults.

CHAPTER 8: EPILOGUE

8.1 Introduction

This thesis presents a series of studies that aimed to develop current understanding of the mutuality between environment and individual, in relation to the successful negotiation of urban challenges to locomotion. This concluding chapter aims to summarise the main findings from the thesis. First, I will provide an outline of the key findings emerging from the experimental chapter. Next, the implications of these findings relevant to both public safety and the wider literature base shall be discussed. Finally, I will focus on detailing the implications of this work and direction for further study.

8.1.1 The current thesis

This thesis entailed the study of perceptual-motor control as participants overcame the challenges associated with stepping onto moving surfaces, such as escalators. Accordingly, accurately capturing participants perceptual-motor behaviours in a moving surface experimental setting required a method that enabled gaze and kinematic behaviours to be expressed in relation to the laboratory environment. This requirement was met though the development of an optoelectronic motion capture and mobile eye tracking integration (Chapter 4), which enabled participants point of gaze to be expressed within the laboratory's coordinate system. Moreover, the integration enabled greater automation of the analysis of eye movements, which in turn greatly increased the efficiency of data analysis compared to 'traditional' frame-by-frame coding methods. To ensure the integration presented a viable means of accurately collecting participants behaviours when overcoming environmental challenges, the quality of gaze data - collected while participants viewed ground based targets at distances of 1-6m, as common during locomotor pointing research (Cornus, Laurent, & Laborie, 2009; Lee, Lishman, & Thomson, 1982; Montagne et al., 2000; van Andel et al., 2018) was examined. This analysis highlighted that the accuracy and precision of gaze data was significantly reduced at viewing distances of greater than 3m. Although this result revealed a consideration for alternative locomotor paradigms, the short approach distances of 2m associated with stepping onto a moving surface indicated the integration presented a viable method of collecting perceptual-motor behaviour during subsequent experiments (Chapters 5 to 7). These experiments aimed to explore how younger (18-40 years) and older (>60 years) adults stepped onto static and moving surfaces, with and without accuracy demands (Chapter 5); how current escalator safety interventions - high contrast demarcation lines and foot targets, positioned on the moving surface - influenced younger and older adult behaviours (Chapter 6); and finally whether a new intervention - a high contrast target line positioned on the approach to the moving surface - could promote safer locomotion (Chapter 7).

These experiments revealed that participants perceptual-motor behaviours differed between experimental conditions. Specifically, Chapter 5 showed that both younger and older participants increased step length when stepping onto moving, rather than static, surfaces (younger adults: 62.9cm and 68.6cm; older adults: 59.1cm and 62.0cm; static and moving surfaces respectively) but reduced step length when experimental conditions demanded accurate movement (younger adults: 67.8cm and 63.8cm; older adults: 63.3cm and 59.8cm; no accuracy and accuracy demand respectively). Furthermore, participants transferred their gaze away from the final walkway footstep location - prior to foot contact - significantly later when stepping onto a moving surface with high contrast lines and/or foot targets compared to moving surfaces with low contrast demarcation lines and no foot targets (Chapter 6). Behaviours also differed between high contrast demarcation and foot target conditions, with foot targets inviting behaviours such as increased step time variability (M = 0.17s for conditions without foot targets and 0.19s for conditions with foot targets), indicating increased online control. Finally, in Chapter 7 participants increased toe distance - measured horizontally as the distance between the belt surface threshold and the front edge of the supporting foot - when a target line was added to the walkway (*M* = 7.8cm and 15.7cm for no approach target and approach target conditions, respectively).

The findings across these experiments also revealed that the behaviours of younger and older adults often differed. Specifically, comparisons between moving and static surfaces with and without accuracy demands (Chapter 5) identified that across the four experimental conditions older adults transferred gaze from the final step on the approach walkway location between 464ms and 266ms earlier than younger adults. Furthermore, between subject effects indicated that older adult approach time variability (between 150ms and 250ms) was greater than younger adults (between 110ms and 130ms) when overcoming conditions with or without high contrast demarcation lines or foot targets (Chapter 6). Such behaviours were interpreted as evidencing a greater use of feed-forward control and a reduction in online control in older adults. Because different physical and cognitive demands have been associated with online and feed-forward control, this finding indicated that older adults utilised the comparatively less demanding feed-forward control to achieve successful locomotion at lower resource cost.

Comparisons between conditions with or without design interventions (such as: high contrast demarcation lines, foot targets, and approach target lines) revealed that design interventions invited different behaviours in younger and older adults. For example, foot targets added to the moving surface (Chapter 6) invited increased step time variability in younger adults (160ms with foot targets and 200ms without foot targets), yet step time variability was unchanged in older adults (180ms, both with foot targets and without foot targets). Moreover, the approach target line (Chapter 7) invited younger adults to transfer gaze from the final walkway footstep location earlier before foot contact but invited later gaze transfer in older adults (younger adults transferred gaze 332ms and 237ms; older adults transferred gaze 247ms and 447ms before foot contact; no target and target conditions respectively). These behaviour adaptations highlighted that younger adults appeared to be drawn to solicitations for online control to a greater extent than older adults, yet older adults were drawn to solicitations for feed-forward control. Such results suggest that the mutuality between the environment and a person's capacity for action co-determine the behavioural invitations that are extended to an individual.

8.2 Theoretical Implications

8.2.1 Gaze data collection and analysis

The integration of gaze and motion capture (Chapter 4) presented a novel method of collecting and analysing gaze data. Establishing the quality of data collected using this approach enabled a larger volume of gaze data to be analysed that would have been feasible by following the traditional approach of manually coding areas of interest on a frame by frame basis (Holmqvist et al., 2010). To illustrate this point, the results from Chapters five to seven of this thesis are derived from approximately 2.1 million frames worth of gaze data (not including rejected participants or missing data points). The capability to collect and analyse greater volumes of gaze data serves to enhance statistical power, which has been noted as low in research featuring gaze data (Jongerius et al., 2021; Knudson, 2017) and thus has the potential to strengthen future research involving the analysis of perceptual-motor behaviour.

Aside from enhancing the volume of data collected, Chapter 4 highlighted that gaze data quality was reduced at greater look ahead distances. Although distances of less than three meters (which did not significantly impede data quality) were considered throughout this thesis, many studies consider tasks that incorporate larger viewing distances, with locomotor research suggesting that visual information is exploited from distances of 6m preceding a foot target or obstacle (Cornus, Laurent, & Laborie, 2009; Lee, Lishman, & Thomson, 1982; Montagne et al., 2000; van Andel et al., 2018). Accordingly, it would be interesting to directly compare the results of frame by frame analysis (of scene camera footage) to data analysed through the integration. This contribution to the literature would mean that the effect of viewing distance on gaze data quality can be evaluated in data collected using the scene camera, establishing the quality of extant research, as well as comparing data quality between both data collection methods.

8.2.2 Perceptual-motor control and affordances

The overall aim of this thesis is to examine the perceptual-motor behaviours that underpin successful locomotion as younger and older adults negotiate the challenge of stepping onto moving surfaces, and subsequently explore the use of environmental design as a means of soliciting behaviour change. In addressing these aims, the current thesis has explored how perceptually guided action varies between individuals and environments by considering human behaviour from the viewpoints of: affordance based control (Fajen, 2005; 2007), the proposal of affordances as invitations for action (Dreyfus & Kelly, 2007; Withagen et al., 2012), and Withagen and colleagues (2012; 2017) re-conceptualisation of agency. As these concepts had not been examined collectively through the lens of human locomotion, the findings of this thesis contribute to our understanding across these areas.

The concluding remarks of Harrison and colleague's (2016) paper, which aimed to characterise affordance-based control, noted that the study of how perceptually guided action varied between realisations and between individuals presented an avenue for future research. The findings presented in this thesis contribute to developing our understanding within this area and reinforce that the individual-environment interaction influences human behaviour. For example, Chapter five considered the behaviours that enabled successful locomotion as younger and older adults overcame conditions of increasing challenge. Specifically, the chapter showed that: (i) the behaviours participants used to overcome environmental challenges were scaled to the demands of the environment, and (ii) the behaviours used to overcome environmental demands differed between the participants age groups. These findings are consistent with the core concepts of affordance based control which position that individuals perceive the world in terms of the actions they can or cannot perform, with the dynamic properties of their body and the demands of the environment denoting a boundary separating possible and impossible actions (Fajen, 2007).

The findings of Chapter six however may offer a progression which suggests that the realisation of an affordance may not hinge exclusively on whether an action is possible to achieve or not. Specifically, by considering the behavioural adaptations solicited by the interventions of foot targets and high contrast demarcation lines, Chapter six highlighted that older adult participants appeared to decline invitations for online control (Dreyfus & Kelly, 2007). However, this does not mean that online control behaviours were *impossible* for older adults (e.g., Fajen, 2007). Indeed, results suggest that older adults still used online control when overcoming conditions, although to a lesser extent than younger adults. Thus, the invitation for online control may have still been present within the older participants field of affordances (Kiverstein et al., 2019). Extant literature has made a similar observation, with younger and middle aged participants opting to work from different areas within the EoS office. In particular, middle aged participants preferred (but didn't exclusively use) positions that afforded supported leaning, whereas younger adults preferred more reclined positions (Caljouw et al., 2019; Withagen & Caljouw, 2016). Such observations support Withagen and colleagues (2012; 2017) suggestion that an individual's capacity to modulate the strength of the coupling between individual and environment shapes human behaviours by allowing individuals to influence the extent to which they are drawn to different affordances. Similarly, the results from the current thesis indicate that rather than action capabilities dictating a polarised ‘possible or impossible’ approach to action (e.g., Fajen, 2007), the attraction of affordances may be influenced by (amongst other things) how proximal the realisation of an affordance my place an individual to the limits of their action capabilities. Thus, in the context of the adaptive locomotion literature, affordances that invite adaptations that increase physical and cognitive demand may appear less attractive to at risk populations, such as older adults.

Although the points raised above may be indicative of why feed-forward control behaviours emerged in older adults (Chapter 5 & 6) they do not fully account for why younger adults still utilised online control behaviours when, as demonstrated by older adults, environmental challenges could be overcome at a lower physical demand by exploiting feed-forward control. Moreover, such behaviours seem contrary to human predisposition for efficient motion (Hayhoe & Matthis, 2018; Selinger et al., 2015). Away from the moving surface paradigm studied in the current thesis, one possible explanation may be offered by considering literature (e.g., Montagne et al., 2000b) exploring the relationship between the amount of adjustment required when making accurate movements (such as the locomotor pointing task of long jumping, or accurately hitting a table tennis ball) and the spatiotemporal control of when behaviour adaptions were initiated. Researchers in this area have suggested that the pick-up of information could be described as ‘funnel-like’ (Bootsma et al., 1991; Montagne et al., 2000b), with the need to adapt behaviour becoming evident as the error approaches the tolerance of the system, which reduces as the athlete approaches the foot target. This interpretation explains why larger errors are detected and corrected earlier during the approach to the long-jump foot target. In the same way, and borrowing Montagne and colleagues (2000b) terminology, the demands of online control may have been perceived as threatening the tolerance in the system (e.g., an individual’s action capabilities) which, based on the diminished action capabilities associated with advancing age, would have led to earlier detection by older adults.

Alternatively, for younger adults, this may mean that online control might have not threatened the greater tolerance in their perceptual-motor system to the same extent, thus, online control may have remained attractive for longer (see also: Chapman & Hollands, 2007; Roos et al., 2010). Future research may wish to gather empirical support by evaluating the behaviours of individuals as new invitations are added their field of affordances, thus determining if behaviour change occurs independently to the possibility of action.

8.3 Practical implications

8.3.1 Moving surface safety

Stepping onto an escalator's surface presents a challenge to successful locomotion that is encountered on a daily basis by many urban dwelling people. As such, escalators present a challenge that directly threatens the health of members of the public (Beards et al., 2022). Despite research recognising escalators as a cause of injury (Schminke et al., 2013), the behaviours associated with stepping onto moving surfaces have received limited empirical attention (Beards et al., 2022; Hsu et al., 2015). Moreover, interventions designed to improve escalator user safety have been largely informed by staircase design and had been previously untested in a moving surface environment (d2e, 2018). The chapters presented within this thesis address such issues by exploring and developing interventions that influence public safety. As such, several practical implications have emerged from this body of work that may have real-world impact, these shall be outlined below.

Chapters six considered the use of environmental design as a means of soliciting behaviour change and evaluated two interventions currently applied to escalator surfaces to improve user safety. The results presented in this chapter have perhaps the most meaningful practical significance regarding public safety, and echo points raised in staircase literature that demand researchers empirically evaluate factors that influence public safety rather than rely on ‘common sense’ (Foster et al., 2014; Simoneau et al., 1991). Firstly, Chapter six highlights that manipulating environmental features (the contrast of demarcation lines or including foot targets) invites specific perceptual-motor adaptations that differed relative to the age group of the participants. This finding is important as it supports the use of environmental design as a method of improving user safety. Secondly, results from chapter six show that increasing the salience of visual information (e.g., high contrast demarcation lines or foot target conditions) enhanced environmental certainty and enabled feed-forward control related behaviour adaptations that promoted successful locomotion. This finding is consistent with stair based literature (Thomas et al., 2021; Zietz et al., 2011), and literature indicating participants adapt their locomotor behaviours to enhance environmental certainty when negotiating rough terrains (Matthis et al., 2018). Finally, chapter six also showed that behaviours differed between demarcation line and foot-target interventions. Although both interventions enhanced salience, foot targets invited behaviours consistent with online control in younger adults. Such adaptations have been associated with increased physical demand. Interestingly, age group related effects suggest that as action capability decreases the allure of an intervention to solicit more demanding behavioural changes may be diminished, with older adults proving resistant to invitations for online control. Overall Chapter six implies that interventions that increase environmental certainty may improve safety, but interventions such as foot targets may have limited benefit for older adult pedestrians in moving surface environments.

Chapter seven aimed to develop an intervention that may improve escalator safety and showed that a high contrast line placed on the approach prior to the moving surface influenced the behaviours of younger and older adults. The approach target line invited feed-forward control throughout the step onto the moving surface, indicating that participants stepped onto the moving surface more efficiently. Furthermore, the approach target increased the horizontal distance between the toe of the supporting limb and the moving surface in both younger and older adults. This adaptation is particularly important as the chance of participants supporting foot overlapping the moving surface participants was reduced, lessening the risk of miss-stepping occurring. Overall, these behaviour adaptations suggest that a target line positioned at the penultimate step location may offer a method of promoting escalator safety.

The results presented in this thesis showed that environmental design provides a method of inviting potentially safer, adaptive behaviours. Therefore, there are several implications that must be considered when translating these findings into practice and industry settings. In particular, experimental findings within extant literature (Withagen & Caljouw, 2016; Zietz et al., 2011) and the results from Chapters 5, 6 and 7 revealed that a person's action-capabilities and environmental characteristics shape the affordances that show-up to each individual. This finding is particularly important for health and safety professionals - who have been acknowledged as 'borrowing' interventions from stair-based settings to improve escalator safety (CIBSE, 2015; d2e, 2018) - as it highlights that the capacity to generalise results between different settings (such as stair and escalator use) or between different populations (such as younger and older adults) is limited.

The findings from this thesis also highlighted that although interventions such as approach markings did invite adaptive behaviours and showed the potential to improve public safety, the behaviours invited by such interventions must be evaluated outside of the laboratory environment, before use in public locations can be justified. However, there are several challenges associated with measuring perceptual-motor behaviours outside of the laboratory that are amplified when attempting to measure human behaviour in public settings (e.g., sensitivities in measurement equipment; physical space, public safety, and electrical power supply constraints). These factors present multiple challenges that reduce the accuracy of both gaze and kinematic measurements as well as the efficiency of the data analysis process (Hessels et al., 2018; van der Kruk & Reijne, 2018). Because of these issues, researchers may first wish to determine if a design intervention has the potential to improve public safety by utilising a lab-based paradigm to capture a portfolio of perceptual-motor adaptations solicited by an intervention (e.g., Thomas et al., 2020; Thomas et al., 2021) before subsequently using a selection of key variables to evaluate the perceptual-motor adaptations solicited by an intervention outside of the laboratory setting.

8.4 Considerations for future research

The results and discussions contained within this thesis have presented numerous considerations for future research that relate to the areas of perceptual-motor behaviour as well as data collection and analysis. Many suggestions for further research have been made, however, there are a couple of additional areas that may be of interest.

8.4.1 Measuring action capabilities

Fajen's (2005, 2007) affordance based control has been at the core of this thesis. As such, one key aspect that merits future consideration is how best to differentiate between people's action capabilities when studying older and younger adult populations in locomotor research. Although categorisation based on age group and questionnaire measures give an indirect indication of people's action capabilities (as supported by the behaviour differences emerging between participant groups), they do not provide a direct measurement of action capability. Furthermore, action capabilities have been shown to be temporal (e.g., fatigue), body (e.g., limb length) and action specific (e.g., limb strength) as well as relative to the qualities of performance environment, such as ground condition (Fajen et al., 2008; Konczak et al., 1992; Warren, 1984; Warren & Whang, 1987).

Previous research has applied maximum effort based approaches to quantify participants action capabilities. For example, Pijnappels and colleagues (2007) searched for muscle strength measures that best idented individuals who would fall when subjected to a perturbation caused by catching the subject’s left swing leg during mid-swing. The authors found that maximum isometric push-off force in a leg press apparatus and maximal jumping heights were able to identify high fall risk older adults. Similarly, Dicks et al., (2010) recorded football goalkeepers movement times in order to measure the action capabilities. To establish these characteristics, goalkeepers had to reach six predetermined locations with movement times being used to classify participants movement capabilities. However, such approaches may be limited when considering that action capabilities vary over time (Fajen et al., 2009). Moreover, unlike overcoming a prescribed perturbation (Pijnappels et al., 2007), saving a penalty kick (Dicks et al., 2010), which incur a threshold separating success and failure (e.g., participants were strong enough to recover from perturbation, or fast enough to intercept the penalty kick), pedestrians negotiate environments that present a vast landscape of affordances. That is to say, there is an abundance of potential actions that enable pedestrians to reach their destination without surpassing their capabilities (Rietveld & Kiverstein, 2014). For example, a pedestrian approaching an escalator with insufficient speed to reach a step can achieve successful performance by waiting for the next step to appear, whereas an outfielder chasing a flyball with insufficient speed cannot achieve success (e.g., Postma et al., 2017). Although multiple affordances are present within locomotor environments, the reduced action capabilities associated with older adults indicates an environments afford fewer opportunities for action to older populations (Montagne et al., 2000b). Accordingly quantifying the limits of an individual’s capabilities in locomotor settings, may allow future researchers greater clarity regarding human perceptual-motor behaviours utilised throughout locomotor tasks. Furthermore, the ability to classify action capabilities provides a key step towards the capacity to prospectively identify adults at greatest risk of fall; a prospect that has been considered a ‘holy grail’ of fall research (see: Hausdorff, 2005).

8.4.2 Manipulating an individual’s action capabilities

The concept that action capabilities are not constant but change on a moment by moment basis (e.g., Fajen et al., 2009) merits further exploration. For example, physiological condition such as fatigue, hypothermia or hypoxia have all been shown to effect human performance (Armstrong, 1999). However, studies evaluating the changes to perceptual-motor behaviour under such conditions are scare (Peißl et al., 2018). Such an omission is surprising as numerous fatalities have been associated with the decline in performance (both physical and cognitive) as humans negotiate rough terrain under such conditions. For example, profound fatigue, cognitive changes and loss of motor control (Ataxia) have been noted as the predominate symptoms in non-surviving Everest climbers (Firth et al., 2008). It would be an interesting evaluation of affordance based control in adaptive locomotion to consider how the behaviours of an individual alter as their action capabilities are gradually degraded. Such an experiment could shed light on the relationship between action capabilities and the appeal of affordances buy considering how an individual (rather than distinct groups of individuals) adapts their perceptual-motor behaviours.

8.4.3 Limitations

Further considerations for future research can be identified by acknowledging several of the limitations within this body of work. First, the participants examined in Chapters 5, 6, and 7 were recruited based on age groupings, with participants considered at high risk of fall being excluded. This decision was necessitated by ethical constraints, which are consistently acknowledged in previous adaptive locomotion literature (e.g., van andel et al., 2018). Given that the behaviours of low and high fall risk older adult groups have been shown to differ (Chapman & Hollands, 2007), future research may wish to expand on the scope of this thesis by investigating the behaviours of high fall risk older adults whilst controlling for the increased consequence of maladaptive behaviours associated with this frail population (Beards et al., 2022; Maki, 1997). Previous research exploring the behaviours of high fall risk populations associated increased injury likelihood and severity have alleviated injury risk through the use of less demanding tasks (e.g., Ellmers et al., 2020) or supportive harnesses (e.g., Liu et al., 2017), however, such approaches hinder environmental representation and reduce the capacity to apply findings outside of the laboratory settings (Brunswik, 1956).

Second, extant literature has applied event classification algorithms to eye orientation signal to classify perceptual-motor behaviour (such as fixations and saccades) during adaptive locomotor tasks (e.g., Ellmers et al., 2019; Thomas et al., 2021). However, this approach was considered not feasible within the current thesis because these approaches do not account for disparity between the participant's eye and bodily motion (Hessels et al., 2018; Lappi, 2015). Alternative approaches to classify gaze behaviours have utilised manual frame by frame analysis to code gaze locations, classifying fixations as a period in which participants dwell on a single location for a period of 3 consecutive frames or longer (equating to a period of 90ms; Kal & Ellmers, 2020). Although automating this process is possible, the relationship between viewing distance and reduced data quality (which resulted in poor precision and accuracy; Chapter 4) coupled with a low sampling rate of the eye-tracking system (i.e., 50hz) inhibited accurate event classification in relation to areas of interest in the environment. Future research would benefit from exploring the use of the motion capture-eye tracking integration to develop algorithms that accurately classify gaze behaviours within a world reference frame and thus overcome the limitations associated with the separate movements of the eye and body.

Third, Chapters 5, 6, and 7 highlighted that people overcame environmental challenge using a synergy of online and feed-forward control. Throughout this thesis, online behaviours were considered to be adaptations made throughout the step onto the conveyor belt surface (e.g., concurrent movement), and feed-forward behaviours were considered to be made throughout the approach phase. Although a synergistic relationship between these control modes has been recognised in previous research (Barton et al., 2017), it is often not immediately clear how changes identified across perceptual-motor variables relate to each control mode. For example, the penultimate step location has been recognised as important when overcoming obstacles and moving surfaces (Chapter 7; Barton et al., 2017; Matthis et al., 2017), with a reduction in penultimate step variability (e.g., toe distance variability) being associated with increased feed-forward control. However, it is also plausible that the reduced penultimate step variability is realised through the use of online control. As such, future researchers may benefit from further investigation designed to specify which variables, or interactions between variables, are associated with each control mode.

Finally, the sample size criteria used throughout the thesis was established using effect sizes presented in research pertaining to adaptive locomotor behaviours (e.g., Chien et al., 2018; Ellmers et al., 2016; Matthis & Fajen, 2012, 2014; Matthis et al., 2015; Muroi & Higuchi, 2017). This method has been commonly applied throughout experimental literature (Lakens, 2021), however, the findings presented through this thesis highlight that both a person's action-capabilities and environmental demands influenced perceptual-motor behaviours. Such findings imply that using the effect sizes presented in research examining the behaviours of different populations or the behaviours observed as participants negotiated different locomotor challenges may limit the accuracy of using such data to calculate power or sample size. To overcome this limitation, future research may promote clarity by justifying why the selected effect size may be appropriate to calculate sample sizes for the current research (Lakens 2021) or by calculating sample size based on the smallest expected effect size (Lakens 2022). Moreover, taking these steps may help to promote clarity around sample justification, which has been identified as poor throughout sport and movement science literature (Abt et al., 2020).

8.5 Conclusion

This thesis developed an integration of optoelectronic motion capture and eye tracking in order to undertake a series of experiments comparing the behaviours of younger and older adults across a range of experimental conditions that simulated an escalator environment. Subsequent experiments then provided insight into how younger and older adults adapted their perceptual-motor behaviours when design interventions - intended to improve pedestrian safety - were added to the simulated escalator environment. Such comparisons enabled the evaluation of design interventions and ultimately suggested that: (i) adaptive perceptual-motor behaviours were specific to both the participants age associated action capabilities and the properties of the environment; (ii) older adults did not appear to utilise interventions such as foot targets that were added to the moving surface as they had the function of inviting more physically demanding online control; (iii) both younger and older adults were drawn to interventions, including high contrast demarcation lines added to the moving surface, and a high contrast foot target line positioned on the approach to the moving surface, that invited feed-forward control. As such, interventions that invite feed-forward control may reduce the functional demand of successful locomotion and be attractive to pedestrians; particularly those with reduced action capabilities. These findings have clear implications for public safety with considerations for an escalator context and emphasise that care must be taken to ensure that the demands of realising a design intervention do not increase the functional demands on a pedestrian's action boundaries.

From a theoretical viewpoint, the works presented through this thesis have consistently aligned with affordance based control (Fajen 2005; 2007) and support the premise that people act in ways that may be scaled to their action capabilities. As such, this work provides, to my knowledge, the first account of affordance based control being evident as people overcome locomotor challenges and provides new insight into person-environment interactions that extends into effective environmental design with implications for public health and safety settings.

CHAPTER 9: REFERENCES

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CHAPTER 10: APPENDIXES

Appendix 1: Ethical approval Chapter 4, 5 and 6

UNIVERSITY OF PORTSMOUTH

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Mr Rhys Hunt
Department of Sport & Exercise Science
University of Portsmouth

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01 August 2018

FAVOURABLE ETHICAL OPINION – FOLLOWING RESUBMISSION

Study Title: An examination of eye and foot movements when stepping onto static and moving surfaces.

Reference Number: SFEC 2018-074

Date Resubmitted: 27 July 2018

Thank you for resubmitting your application to the Science Faculty Ethics Committee (SFEC) for ethical review in accordance with current procedures, for making the requested changes following the first SFEC review, and for the clarifications provided.

I am pleased to inform you that SFEC was content to grant a favourable ethical opinion of the above research on the basis described in the submitted documents listed at Annex A, and subject to standard general conditions (*See Annex B)*.

Please note that the favourable opinion of SFEC does not grant permission or approval to undertake the research. Management permission or approval must be obtained from any host organisation, including the University of Portsmouth or supervisor, prior to the start of the study.

Wishing you every success in your research

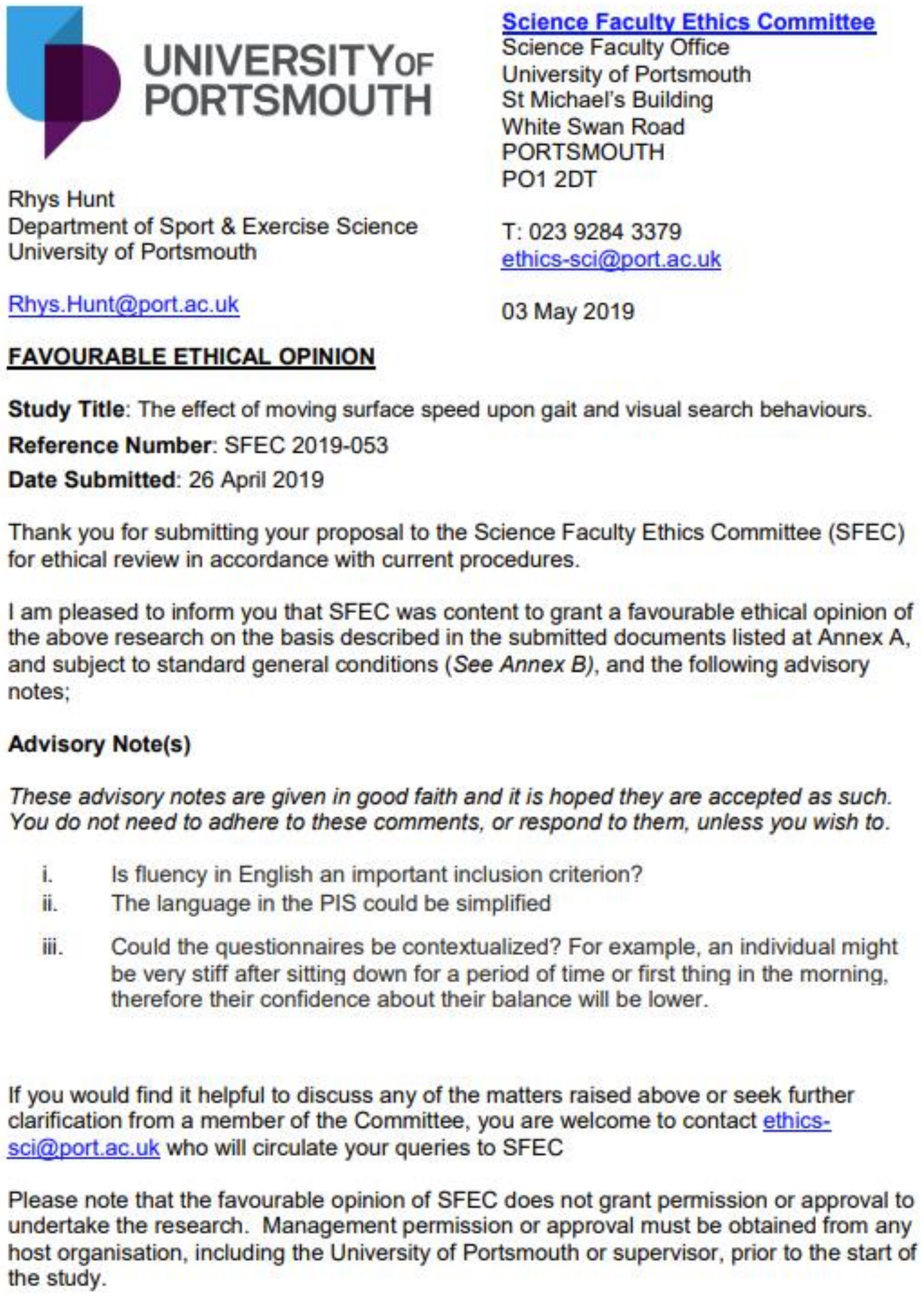
Dr Paul Morris
Vice Chair, Science Faculty Ethics Committee

Annexes

A - Documents reviewed
B - After ethical review - Guidance for researchers

Information:

Appendix 2: Ethical approval Chapter 7



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03 May 2019

FAVOURABLE ETHICAL OPINION

Study Title: The effect of moving surface speed upon gait and visual search behaviours.

Reference Number: SFEC 2019-053

Date Submitted: 26 April 2019

Thank you for submitting your proposal to the Science Faculty Ethics Committee (SFEC) for ethical review in accordance with current procedures.

I am pleased to inform you that SFEC was content to grant a favourable ethical opinion of the above research on the basis described in the submitted documents listed at Annex A, and subject to standard general conditions (*See Annex B)*, and the following advisory notes;

Advisory Note(s)

These advisory notes are given in good faith and it is hoped they are accepted as such. You do not need to adhere to these comments, or respond to them, unless you wish to.

i. Is fluency in English an important inclusion criterion?
ii. The language in the PIS could be simplified
iii. Could the questionnaires be contextualized? For example, an individual might be very stiff after sitting down for a period of time or first thing in the morning, therefore their confidence about their balance will be lower.

If you would find it helpful to discuss any of the matters raised above or seek further clarification from a member of the Committee, you are welcome to contact ethics-sci@port.ac.uk who will circulate your queries to SFEC

Please note that the favourable opinion of SFEC does not grant permission or approval to undertake the research. Management permission or approval must be obtained from any host organisation, including the University of Portsmouth or supervisor, prior to the start of the study.

FORM UPR16

Research Ethics Review Checklist

Please include this completed form as an appendix to your thesis (see the Research Degrees Operational Handbook for more information

Postgraduate Research Student (PGRS) Information		**Student ID:**	887677
PGRS Name:	Rhys Hunt		
Department:	SSHES	**First Supervisor:**	Dr Matt Dicks
Start Date: (or progression date for Prof Doc students)	FEB 2018		
Study Mode and Route:	Part-time ☐ Full-time ☒	MPhil ☐ PhD ☐	MD ☐ Professional Doctorate ☐

Title of Thesis:	An examination of adaptive behaviour when stepping onto moving surfaces: an affordances and agency perspective
Thesis Word Count: (excluding ancillary data)	53423

If you are unsure about any of the following, please contact the local representative on your Faculty Ethics Committee for advice. Please note that it is your responsibility to follow the University's Ethics Policy and any relevant University, academic or professional guidelines in the conduct of your study

Although the Ethics Committee may have given your study a favourable opinion, the final responsibility for the ethical conduct of this work lies with the researcher(s).

UKRIO Finished Research Checklist:
(If you would like to know more about the checklist, please see your Faculty or Departmental Ethics Committee rep or see the online version of the full checklist at: http://www.ukrio.org/what-we-do/code-of-practice-for-research/)

a) Have all of your research and findings been reported accurately, honestly and within a reasonable time frame?	YES ☒ NO ☐
b) Have all contributions to knowledge been acknowledged?	YES ☒ NO ☐
c) Have you complied with all agreements relating to intellectual property, publication and authorship?	YES ☒ NO ☐
d) Has your research data been retained in a secure and accessible form and will it remain so for the required duration?	YES ☒ NO ☐
e) Does your research comply with all legal, ethical, and contractual requirements?	YES ☒ NO ☐

Candidate Statement:

I have considered the ethical dimensions of the above named research project, and have successfully obtained the necessary ethical approval(s)

Ethical review number(s) from Faculty Ethics Committee (or from NRES/SCREC):	SFEC 2018-074 & SFEC 2019-053

If you have *not* submitted your work for ethical review, and/or you have answered 'No' to one or more of questions a) to e), please explain below why this is so:

Signed *(PGRS)*:	Rhys Hunt	**Date:** 25/01/2022