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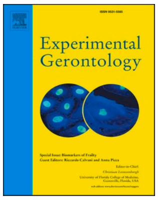

The visual control of locomotion when stepping onto moving surfaces: A comparison of younger and older adults

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ABSTRACT

Stepping between static and moving surfaces presents a locomotor challenge associated with increased injury frequency and severity in older adults. The current study evaluates younger and older adults' behaviours when overcoming challenges sampling moving walkway and escalator environments. Twelve younger adults (18–40 years, Male = 8) and 15 older adults (60–81 years, Male = 5) were examined using an integration of opto-electronic motion capture and mobile eye-tracking. Participants were investigated approaching and stepping onto a flat conveyor belt (static or moving; with or without surface (demarcation) lines). Specifically, the four conditions were: (i) static surface without demarcation lines; (ii) static surface with demarcation lines; (iii) moving surface without demarcation lines; and (iv) moving surface with demarcation lines.

A two (age group) x two (surface-condition) x two (demarcation-condition) linear mixed-model revealed no main or interaction effects ($p > .05$) for perturbation magnitude, indicating participants maintained successful locomotion. However, different adaptive behaviours were identified between conditions with moving and accuracy demands (e.g., moving surfaces increased step length, demarcations reduced step length). Between subject effects identified differences between age groups. Older adults utilised different behaviours, such as earlier gaze transfer from the final approach walkway step location. Overall, the current study suggests that adaptive behaviours emerge relative to the environment's specific demands and the individual's action capabilities.

1. 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). For example, 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 or adapt movement (Matthis and 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 changes in locomotor and gaze behaviours to reduce gait perturbations (Higuchi, 2013a, 2013b; Wu et al., 2017). Urban environments in particular receive high numbers of pedestrians and contain numerous challenges, with examples including: negotiating closing apertures (Cinelli and Patla, 2008); avoiding other pedestrians (Dicks et al., 2016); and stepping onto moving surfaces, such as moving walkways and escalators (Hsu et al., 2015).

In experimental laboratory settings, researchers have primarily explored adaptive locomotor behaviours by manipulating environmental constraints such as limiting foot holds, adding obstacles, or including foot-targets; all of which require accurate movements (for reviews, see Barton et al., 2017; Higuchi, 2013a, 2013b). Studies have reported consistent perceptual-motor adaptations that are proportionate to increasing accuracy demands (Domínguez-Zamora et al., 2020; Marigold and Patla, 2007, 2008a, 2008b), such as increased approach times, reduced stride lengths, and slower step speeds (Swart et al., 2020). Whilst such research has enriched current understanding, it has been suggested that paradigms, which place very specific demands of human behaviour, such as accurate stepping, may not represent how people overcome the diverse locomotor challenges encountered throughout daily activity (Lappi and Mole, 2018; van Andel et al.,

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2018a, 2018b). Akin to such suggestions, there have been minimal attempts to study the perceptual-motor behaviours of pedestrians negotiating environments that do not specify accurate foot positioning. One such example is the locomotor challenge of stepping onto a moving surface, where pedestrians can achieve successful locomotion by positioning their foot in a range of locations on (or even overhanging) a steps surface (Hsu et al., 2015).

Research investigating escalator injuries has indicated that there are approximately 2600 annual incidents that result in hospitalisation in the US (O'Neil et al., 2008), and a UK based investigation of escalator incidents revealed that there were 403 serious but non-fatal incidents recorded within a one year period (Beards et al., 2022). Falling when stepping onto a moving surface has been recognised as a prevalent cause of injury, with incidents most likely to occur for older adults due to age-related reduced mobility (Beards et al., 2022; Schminke et al., 2013). Although these works highlight that stepping onto moving surfaces presents a challenge to members of the public, the perceptual-motor behaviours that enable older or younger pedestrians to negotiate moving surfaces have yet to be examined. Therefore, in order to address the need to sample daily locomotor challenges (e.g., van Andel et al., 2018a, 2018b) and to enhance understanding of the behaviours that enable successful locomotion across pedestrians with differing mobility capabilities (Beards et al., 2022), the current study will set out to examine the perceptual-motor behaviours of pedestrians negotiating moving surfaces.

1.1. *Affordance-based control*

There is a long history of research exploring the visual control of action (Gibson, 1958; Lee et al., 1982; Warren, 1998) with multiple studies focusing on the scaling between affordances (e.g., possibilities for action) and an individual's action capabilities (Van Andel et al., 2017). One account of visually guided action that has begun to receive increased consideration in the literature is Fajen's (2005a, 2005b) affordance-based control, which 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 (2005a, 2005b) 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, 2005a, 2005b). 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 et al., 2003; Uiga et al., 2015). Specifically, studies comparing younger and older adults commonly report reduced action capabilities with advancing age. For instance, factors that 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 and Bautmans, 2014), as well as inhibited range of motion (Kovacs, 2005). Accordingly, younger and older adults have been compared when negotiating various environmental challenges (Chapman and Hollands, 2007; Muir et al., 2015; van Andel et al., 2018a, 2018b). Findings have revealed changes in older adult kinematics including reduced step length and gait speed, which are thought to proactively mitigate against perturbations and commonly referred to as symptoms of a 'cautious gait' (Kal and Ellmers, 2020; Swart et al., 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, as 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).

1.2. *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 and Marigold, 2019; van Andel et al., 2018a, 2018b). During locomotor tasks that require accuracy in stepping actions, participants have been found 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 distance that gaze is oriented along the travel path (Domínguez-Zamora and Marigold, 2019; Ellmers et al., 2020; Matthis et al., 2018). Fajen and Colleagues (e.g., Barton et al., 2017; Fajen and Warren, 2007; Matthis et al., 2017) have interpreted these findings as evidence of online control, which entails the regulation of concurrent movements, such as actively guiding the foot onto a target mid-stride. In contrast, these same authors have highlighted that locomotor adaptations can be regulated by feed-forward control. For example, studies reporting increased look-ahead distances and earlier gaze transfer times away from proximal locations indicate that walkers can adapt foot position by manipulating centre of mass (COM) trajectory over several steps rather than exclusively on a step-by-step basis (Barton et al., 2019; Matthis and Fajen, 2014). In line with these perspectives, the current study defines online control as adaptations made to concurrent movement and feed-forward control[1] as adaptations made during the approach (e.g., prior to the step negotiating an obstacle). 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 and Hollands, 2007; Domínguez-Zamora et al., 2020; Ellmers et al., 2020). Specifically, it has been suggested that online control is more physically and cognitively demanding than feed-forward control (Ellmers et al., 2020; Ellmers and Young, 2019; Holtzer et al., 2015). The emergence of feed-forward adaptations may reflect the sensitivity of older adults to their action capabilities, with such calibration enabling older adults to maintain successful locomotion without surpassing the 'safe-region' of their action boundaries (Fajen, 2007).

1.3. *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 published 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 locomotor control when stepping onto four conditions of varying difficulty:

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[1] Different definitions of feed-forward control have been used across adaptive locomotor literature, such as those centred on internal representations of the body and required movement patterns (e.g., Tseng et al., 2010).

(i) static surfaces without demarcation lines (e.g., no moving surface or accuracy constraints); (ii) static surfaces with demarcation lines; (iii) moving surfaces without demarcation lines; and (iv) moving surfaces with demarcation lines (e.g., moving surface with accuracy constraints).

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 (e.g., if visual information was exploited over several steps rather than a step-by-step basis) when overcoming conditions of increasing difficulty, the following changes were expected during the approach to the moving surface: significantly reduced toe distance variability between the toe and the edge of the moving surface 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 and Hollands, 2007; Domínguez-Zamora et al., 2020); reduced attention to proximal locations during the approach (Chapman and Hollands, 2006a, 2006b, 2007; Young and Hollands, 2012a, 2012b) and increased gait perturbation (symptomatic of less successful locomotion; Higuchi, 2013a, 2013b). Secondly, it was hypothesised that gait and gaze adaptations would occur 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 (irrespective of age) as participants step onto the belt surface to negotiate more demanding conditions (Swart et al., 2020; Thomas et al., 2020).

2. Methods

2.1. Participants

Research examining how participants overcome the demands of moving surfaces has not previously reported effect sizes. Therefore, the effect sizes presented in literature examining either younger or older adults, or participants overcoming environmental locomotor challenges, were considered to identify expected effect sizes (Lakens, 2022). Authors investigating adaptive locomotor behaviours (Chien et al., 2018; Ellmers et al., 2016; Matthis and Fajen, 2012, 2014; Matthis et al., 2015; Muroi and Higuchi, 2017) have reported 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 age group would be required to obtain 80 % power to detect an effect size of 0.52 (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). Twelve younger adults (18–40 years, Mean (M) = 26.5, Standard deviation (SD) = 5.7 years, Male = 8) and 15 older adults aged over 60 years (60–87 years, M = 71.5, SD = 6.9 years, Male = 5) were recruited from the university and local community. Ethical approval was granted at an institutional level (University of Portsmouth, SFEC 2018-074) with all participants providing signed consent, and establishing the met the exclusion criteria of: no history of falling, physiological impairment, neurological impairment, or non-corrected visual impairment. A questionnaire battery was administered to examine self-reported differences between the two groups (Malhotra et al., 2015; Uiga et al., 2018a, 2018b; Young et al., 2016; Young et al., 2012). The Falls Efficacy Scale - International (FES—I) was selected to provide a measure of fall related concerns (Yardley et al., 2005). The Activities-specific 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 and Myers, 1995); and the Movement-Specific reinvestment scale (MSRS which consists of the dimensions of Movement Self Conscioiusness (MS-C) and Concious Motor Processing (CMP); Masters et al., 2005), which has shown higher scores associated with maladaptive locomotor behaviours (Uiga et al., 2018a, 2018b), questionnaires were completed prior to data collection.

2.2. Apparatus

Fourteen optoelectronic cameras (Oqus 300/310, Qualisys Sweden), sampling at 100 Hz encircled the conveyor belt area ($5 \times 1 \times 2$ m, x, y, z dimensions respectively), which was dynamically calibrated with the marker deviation upper limit of 1.48 mm applied to promote accuracy (Summan et al., 2015). Participants were instrumented with spherical retro-reflective markers (12 mm 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 the footwear and the start of the moving surface (i.e., conveyor belt). A Tobii Pro Glasses 2 mobile eye tracker (Tobii, 2018) and a optoelectronic motion capture system (Qualisys, 2018) were integrated and synchronized to measure point of gaze with a world reference frame (Hunt et al., 2022). Following a one-point calibration of the eye-tracker, which followed Tobii (2018) guidelines, 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 on various locations allowing visual judgement of gaze vector accuracy.

2.3. Procedure

From the same start location, participants were instructed to walk along a two-metre walkway at their own pace, step onto the flat conveyor belt and stand stationary on the belt surface until the end of the trial (trial duration of 8 s). Participants were able to view the required transition prior to the trial commencing and select when they started the approach. In conditions with demarcation lines, participants were informed to avoid contact with the demarcation lines 'as if they were the boundaries of escalator steps' (which on an escalator separate vertically after traveling a horizontal distance of several step lengths). To sample the escalator environment, the height of the approach walkway was flush and bevelled with the conveyor belt surface, alleviating any potential gait inconsistencies induced through changing surface height or negotiating a gap.

Although locomotor pointing literature recognises that pedestrians can adapt their behaviours utilising visual information from distances of between 6 and 8 step lengths prior to a foot target (Hildebrandt and Cañal-Bruland, 2020; van Andel et al., 2018a), an approach distance of two meters was selected based on British Standard requirements (CIBSE, 2015) and expert consultation (d2e, 2018). For example, when using an escalator, people are required to first negotiate factors that occlude the view of the moving surface such as other pedestrians or a barriers (d2e, 2018). To promote a natural gait pattern, participants were able to step onto the belt surface with either foot. Consistent with the most common escalator characteristics in the United Kingdom, the width of the conveyor belt was 1 m, and in the moving condition, the belt was set to move at a constant speed of 0.50 $\mathrm{m.s^{-1}}$ (CIBSE, 2015; Fig. 1).

Four conditions were tested, with the conveyor belt surface being either static or moving and with or without demarcation lines. Specifically, the four conditions were: (i) static surface without demarcation lines; (ii) static surface with demarcation lines; (iii) moving surface without demarcation lines; and (iv) moving surface with demarcation

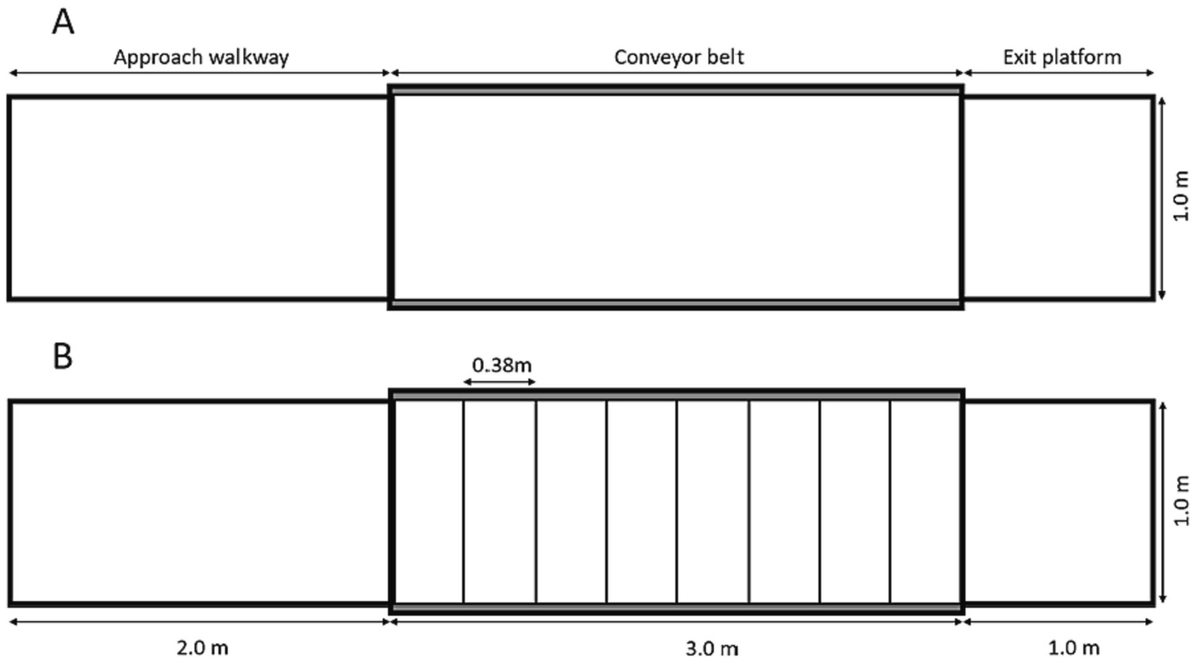

Fig. 1. Top view experimental conditions showing A: dimensions of the approach walkway, conveyor belt and exit platform (left to right respectively). B: Conveyor belt with demarcation lines added.

lines. Condition (i) acted as a baseline condition within the experimental set up. For the no-demarcation condition, no markings were present on the belt surface (Fig. 1A). For the demarcation condition, horizontal high contrast lines were added to the belt surface at 38 cm intervals (Fig. 1B), as per escalator step size (CIBSE, 2015). When the belt was static and demarcation lines were present (condition iii), the first demarcation line was positioned 10 cm from the end the approach walkway. 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 et al., 2012) two younger, and seven older adults required the use of eyeglasses 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 were, however, collected for analysis from all participants.

2.3.1. *Kinematic dependent variables*

As per previous research (Chapman and Hollands, 2006a, 2006b) 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 6 Hz prior to model building and analysis. A CODA Pelvis model was then created using Visual 3D (C-Motion, 2018b). Key gait events (foot contact with the walkway and belt surfaces and toe off's) were identified using a technique utilising the vertical acceleration of heel and toe markers (Hreljac and 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 derived from research detailing that people are sensitive to the minimum approach velocity required to pass through closing apertures (Fajen and Matthis, 2011), and 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 (Fajen and Matthis, 2011; Fajen, 2013); (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 >0.50 m.s^{-1}: Halliday et al., 1998), and foot contact with the belt surface (identified utilising the vertical acceleration of heel and toe markers); and (iii) *Toe distance* (cm), measured horizontally (as per: Madalena et al., 2018; Rietdyk and Rhea, 2006; Zietz et al., 2011) as the distance between the belt surface threshold (e.g., the end of the walkway and start of the belt surface) 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 that supporting foot placement was before the threshold, whereas a negative value indicated that the leading edge of the foot overlapped the end of the walkway.

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), 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).

2.3.2. *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 50 Hz 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 s) were filled via quintic spline interpolation (Hessels et al., 2017; Hunt et al., 2022) The resultant gaze vector's floor intercept was used to compute: (i) *Look ahead distance (m)*, which 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 last time a participant looked at the location of their final step on the walkway and foot contact with this location; (iii) *Belt gaze transfer (s),* was defined as the time difference between the last time a participant looked at the location of their step onto the belt surface and foot contact with this location. 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 each designated AOI was calculated (Hildebrandt and Cañal-Bruland, 2020; Miyasike-Dasilva et al., 2011; Parr et al., 2020). Five 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 3 m 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.

2.4. Statistical analysis

2.4.1. 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 estimated using rank-biserial correlation (r_{rb}) (Kerby, 2014). Bayesian statistics were calculated to evaluate the difference between measures, with the Bayes factor interpreted using thresholds[2] specified by Raftery (1995). Bayesian analysis was conducted using Jamovi (The Jamovi Project, 2020).

2.4.2. Perceptual-motor measures

Linear mixed-effect models were used to examine the perceptual-motor behaviours (Hoffman and Rovine, 2007). The analysis treated participants as random effects and 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. A single model was created for each dependant variable which included main and interaction effects (e.g., Tables 4, 5, and 6). Analysis was undertaken in r (RStudio Team, 2020) using the 'nlme' (Pinheiro et al., 2020), 'ggplot2' (Wickham, 2016) and 'pastecs' (Ibanez and Grosjean, 2018) packages and based on the procedure outlined by Field et al. (2012). Where data were non-normally distributed, significant effects ($p < .05$ was used throughout to indicate statistical significance) were cross checked with robust ANOVAs based on trimmed means (Field et al., 2012; Mair and Wilcox, 2020; Thomas et al., 2021). The results of the robust analyses (where used) did not differ substantially from the linear mixed-effects models, and so only the results from the linear mixed-effects models are presented. Effect sizes were estimated using Pearson's r (*r*) as per the procedure outlined by Field et al. (2012).

2.4.3. 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 affect 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).

Compositional data analysis was undertaken in R (RStudio Team, 2020), using the package 'compositions' (van den Boogaart et al., 2009) and SPSS (SPSS, version 24), and undertaken based on the approaches outlined in previous research (van den Boogaart and Tolosana-Delgado, 2013; Chastin et al., 2015; Gupta et al., 2018; Martín-Fernández et al., 2015). Geometric data were 'closed' to form compositions and transformed using isometric log ratios (ilr), 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]), and 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).

3. Results

3.1. Self-reported measures

Mann-Whitney *U* tests (*U*, Table 1) identified significant differences between age groups in the FES—I, and the ABCs measures. No other significant differences were found between age groups (Table 1). Bayes factors (BF_{10}, Table 1) also indicated moderate evidence ($BF_{10} > 3$) for differences between age groups in measures of falls efficacy and strong evidence ($BF_{10} > 10$) for differences between age groups in measures activities balance confidence.

3.2. Approach variables

Table 2 shows the descriptive statistics of the approach variables by age and experimental condition, and summarises the results of the linear mixed effects models. The detailed results of the linear mixed models are in Tables 4, 5 and 6.

3.2.1. Perturbation magnitude

No significant main effects were identified for surface conditions, demarcation conditions, or age groups ($p > .05$, Table 2). There were no significant interaction effects (all $p > .05$, Tables 4, 5, 6).

3.2.2. Approach time

Significant main effects (Table 2) were identified for demarcation conditions ($p < .001$, $r = 0.74$) and for age groups ($p = .042$, $r = 0.51$). 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 ($p = .007$, $r = 0.35$; Table 5). The interaction effect showed that approach time was significantly greater in older adult participants when stepping onto surfaces with demarcation lines compared to younger adults or participants in no-demarcation line conditions. All other main or interaction effects were non-significant (all $p > .05$, Tables 4, 5, 6).

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[2] Please refer to graph included in the online repository (https://osf.io/uhm6e/).

Table 1
Mean (M) and Standard Deviation (SD) for younger and older participants self-reported characteristics. The table also shows Mann-Whitney U statistic (U); P-Value (p); Rank-biserial correlation (r_{rb}); Bayes factors (BF_{10}).

	Younger		Older					
	M	SD	M	SD	U	p	r_{rb}	BF_{10}
FES-I	18	1.41	20	2.27	40	0.014[a]	0.56	4.134[b]
ABCs	97.20	2.01	92.42	4.81	33	0.006[a]	0.63	11.394[c]
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
MS-C	12.67	6.04	10.67	7.1	65.5	0.235	0.27	0.450

[a] Significant difference ($p < .05$) between age groups.
[b] Moderate evidence for effect.
[c] Strong evidence for effect.

Table 2
Age group and experimental condition comparisons for approach variables (Mean ± Standard Deviation).

	Static		Moving	
	No demarcation	Demarcation	No demarcation	Demarcation
Perturbation magnitude (cm)				
Younger	10.57 ± 2.77	10.60 ± 5.12	9.75 ± 1.88	9.04 ± 1.17
Older	12.17 ± 4.47	11.98 ± 5.95	10.33 ± 2.73	11.70 ± 3.49
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	17.75 ± 10.86	12.55 ± 9.80	11.48 ± 8.30	9.12 ± 9.20
Older	12.48 ± 7.74	8.69 ± 5.92	7.77 ± 5.90	4.02 ± 5.72
Toe distance variability (cm)[b,f]				
Younger	5.27 ± 4.00	3.83 ± 2.56	5.81 ± 3.19	2.66 ± 1.41
Older	6.68 ± 4.41	2.77 ± 1.72	4.57 ± 3.17	2.74 ± 0.84
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 (Static and Moving) conditions. See Table 4.
[b] Significant difference between demarcation (No Demarcation and 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.
[f] Significant three-way interaction between surface, demarcation conditions and age. See Table 6.

3.2.3. *Approach time variability*

A significant main effect (Table 2) showed that older adults approach times were significantly more variable than younger adults ($p = .008$, $r = 0.46$). There were no other significant main effects or interaction effects (all $p > .05$, Tables 4, 5, 6).

3.2.4. *Toe distance*

Significant main effects (Table 2) were identified for surface conditions ($p < .001$, $r = 0.57$) and demarcation conditions ($p < .001$, $r = 0.36$). 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 were no significant between subject, or interaction effects (all $p > .05$, Tables 4, 5, 6).

3.2.5. *Toe distance variability*

A significant main effect (Table 2) showed toe distance variability was reduced when participants had to avoid demarcation lines ($p < .001$, $r = 0.28$). There were no other significant main effects ($p > .05$, Table 4) or two-way interaction effects (all $p > .05$, Table 5) but a significant three-way interaction was identified ($p = .041$, $r = 0.27$). 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.

3.2.6. *Look ahead distance*

Significant main effects (Table 2) were identified for surface conditions ($p = .004$, $r = 0.29$), showing that participant look ahead distance was reduced when stepping onto moving surfaces. A significant interaction effect was identified between surface and demarcation conditions ($p = .004$, $r = 0.15$) 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 4, 5, 6).

3.2.7. *Walkway gaze transfer*

Significant main effects (Fig. 2) were identified for surface conditions ($p = .004$, $r = 0.70$) and for age groups ($p = .008$, $r = 0.53$). These main effects showed that gaze was transferred later 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 4, 5, 6).

3.3. *Final step variables*

3.3.1. *Step length*

Significant main effects (Table 3) were identified for surface conditions ($p < .001$, $r = 0.32$) and for demarcation conditions ($p = .004$, $r = 0.25$). 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 4, 5, 6).

3.3.2. *Step length variability*

A significant main effect (Table 3) was identified for surface conditions ($p < .001$, $r = 0.74$). This main effect evidenced that step length was more variable when stepping onto moving surfaces. There were no significant main effects for demarcation conditions or age groups (both $p > .05$; Table 4). A significant interaction effect between surface and demarcation conditions was identified ($p = .003$, $r = 0.30$). This interaction effect evidenced that the increased step length variability identified in moving compared to static conditions was furthered when

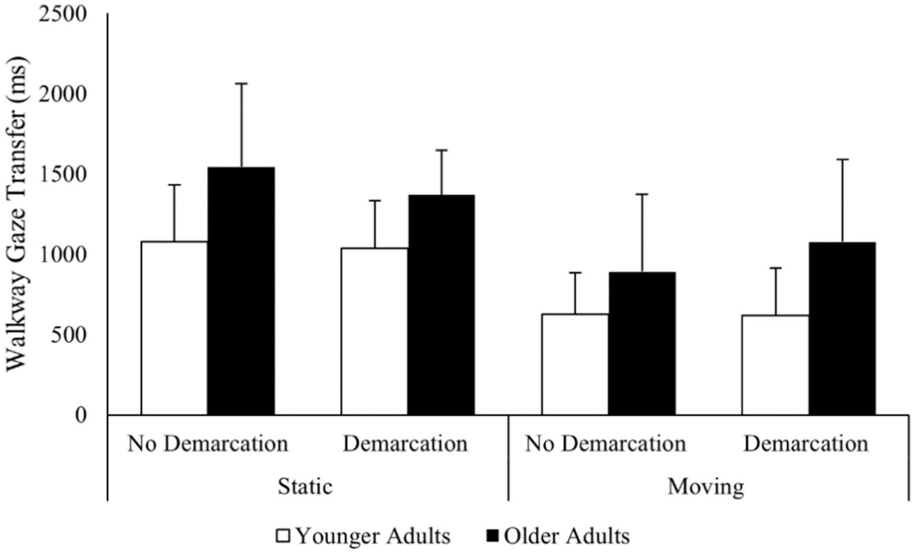

Fig. 2. Mean walkway gaze transfer times (error bars show SD). Significant differences ($p < .05$) were identified between younger and older adults as well as between surface (static and moving) conditions.

Table 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	66.34 ± 10.28	59.50 ± 7.70	69.16 ± 7.88	68.06 ± 7.51
Older	60.34 ± 8.81	57.78 ± 8.73	66.22 ± 9.99	61.81 ± 8.72
Step length variability (cm)[a, c]				
Younger	4.81 ± 2.77	3.48 ± 1.61	7.16 ± 2.21	8.71 ± 2.20
Older	5.36 ± 3.25	3.38 ± 2.66	7.49 ± 2.71	8.56 ± 2.82
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 (Static and Moving) conditions. See Table 4.

[b] Significant difference between demarcation (No Demarcation and Demarcation) conditions. See Table 4.

[c] Significant two-way interaction between surface and demarcation conditions. See Table 5.

demarcations were present on the belt surface. All other interaction effects were non-significant (all $p > .05$, Tables 4, 5, 6).

3.3.3. *Step time*

Significant main effects (Table 3) were identified for surface conditions ($p < .001$, $r = 0.53$) and demarcation conditions ($p = .025$, $r = 0.26$). 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 were no significant between subject or interaction effects (all $p > .05$, Tables 4, 5, 6).

3.3.4. *Step time variability*

No significant main, or interaction effects (all $p > .05$, Tables 4, 5, 6) were found.

3.3.5. *Belt gaze transfer*

Significant main effects (Fig. 3) were identified for surface conditions ($p < .001$, $r = 0.63$) and for demarcation conditions ($p = .044$, $r = 0.28$). 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 4, 5, 6).

3.4. *AOI analysis results*

A repeated measures MANOVA identified main effects for surface condition (F(1,15) 3.915, $p = .029$, $\eta^2 = 0.556$) and a significant interaction effect between age group and surface condition (F(1,15) 8.334, $p = .002$, $\eta^2 = 0.735$). Other main and interaction effects were not significant ($p > .05$). Univariate ANOVA 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, $p = .003$, $\eta^2 = 0.461$). 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 (Fig. 4).

To further explore this main effect, the log ratio for each AOI was plotted for both surface conditions (Fig. 4). Consistent with the results of the univariate ANOVA, 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 ANOVA 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, $p = .012$, $\eta^2 = 0.350$). To explore this effect, the log ratio for walkway and belt was plotted for each age group in both static and moving conditions (Fig. 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.

4. Discussion

Affordance-based control proposes that locomotion is shaped by the relationship between an individual's action capabilities and

Table 4
Main effects for approach variable and final step variables from each linear mixed-effect model. The table shows degrees of freedom (DF), likelihood ratio (χ2), and *P*-value (*p*).

Dependent variable		Surface		Demarcation		Age Groups	
	DF	χ2	p	χ2	p	χ2	p
Approach variables							
Perturbation magnitude	1	2.536	0.111	0.049	0.825	2.312	0.128
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]
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
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]
Final step variables							
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
Belt gaze transfer	1	22.174	<0.001[a]	4.054	0.044[a]	0.928	0.336

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

Table 5
Two-way interaction effects for approach variable and final step variables from each linear mixed-effect model. The table shows degrees of freedom (DF), likelihood ratio (χ2), and P-value (*p*).

Dependent variable	Surface * Demarcation			Age * Surface		Age * Demarcation	
	DF	χ2	p	χ2	p	χ2	p
Approach variables							
Perturbation magnitude	1	0.126	0.722	0.006	0.938	0.415	0.519
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
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
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
Final step variables							
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
Belt gaze transfer	1	0.160	0.689	0.774	0.379	0.149	0.700

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

Table 6
Three-way interaction effects for approach variable and final step variables from each linear mixed-effect model. The table shows degrees of freedom (DF), likelihood ratio (χ2), and P-value (*p*).

Dependent variable	DF	χ2	p
Approach variables			
Perturbation magnitude	1	0.653	0.419
Approach time	1	0.960	0.327
Approach time variability	1	0.844	0.358
Toe distance	1	1.020	0.313
Toe distance variability	1	4.173	0.041[a]
Look ahead distance	1	0.080	0.777
Walkway gaze transfer	1	0.028	0.868
Final step variables			
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
Belt gaze transfer	1	0.471	0.492

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

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 (Chapman and Hollands, 2007). In support of this hypothesis, results indicated that stepping onto moving surfaces or surfaces with demarcation lines (in both surface conditions), resulted in older adults appearing to prioritise feed-forward control. That is, results revealed earlier gaze transfer from the walkway step location in older adults. Moreover, AOI analysis indicated that older adults attended to the walkway less in moving compared to static conditions. Such gaze transfer is in accordance with extant research suggesting that older adult prioritise advanced adaptation to distal constraints at the expense of concurrent movements, a behaviour associated with increased fall risk (Chapman and Hollands, 2007; Ellmers et al., 2020; Young and Hollands, 2012a, 2012b).

Affordance-based control proposes that environmental demand influences behaviour (Fajen, 2007), and therefore the current study compared older and younger adult behaviours across experimental conditions of varying difficulty. Aligning with the second hypothesis, gait and gaze behavioural adaptations associated with increased environmental demand (e.g., moving surface and demarcation conditions) were identified. However, rather than 'cautious gait' behaviours emerging, 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 moving surface compared to demarcation conditions; a finding that will be discussed in greater detail during the discussion (see Tables 2 and 3). Overall, these findings build on extant perceptual-motor control literature and affirms that the synergistic relationship between online and feed-forward control (Matthis et al., 2017) promotes successful

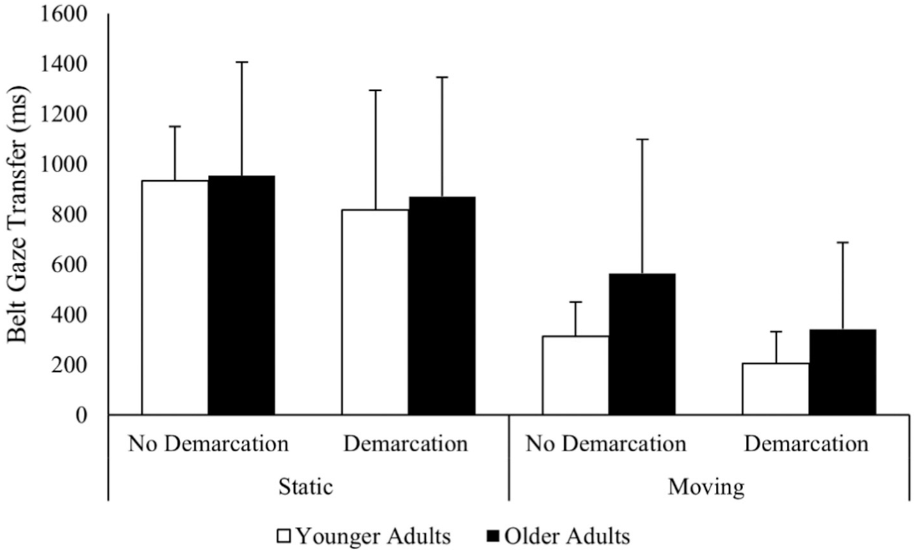

Fig. 3. Mean belt gaze transfer times (error bars show SD). Significant differences ($p < .05$) were identified between surface (Static and Moving conditions) and demarcation (No demarcation and Demarcation) conditions.

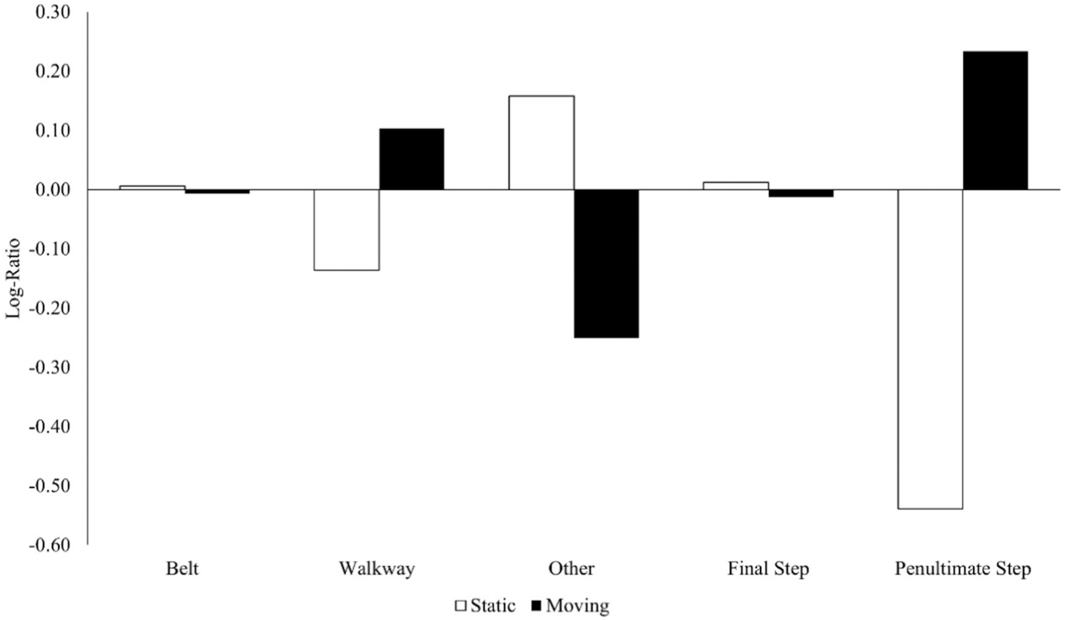

Fig. 4. Areas of interest viewing ratios for static and moving belt conditions. The graph presents the geometric mean expressed in terms of a ratio measured on a logarithmic scale (as expressed on the y axis) to the geometric mean of the entire population for each area of interest. A ratio of 0 reflects 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, respectively. 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 exponential 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.

locomotion even when accurate movement is not demanded.

4.1. Behaviour as a function of age differences

Successful locomotion is achieved by adapting behaviours to reduce perturbation (Higuchi, 2013a, 2013b; Moraes et al., 2007). In the present study, a measure of perturbation magnitude, based on Fajen and Matthis' (2011) 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. All in all, we found older adult behaviours contrast 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., 2018a, 2018b). 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 and Hollands, 2007; Uiga et al., 2015). A likely explanation of the perturbation magnitude measure is that the older adult participants in the current study were of a low fall-risk group. Alternatively, the lack

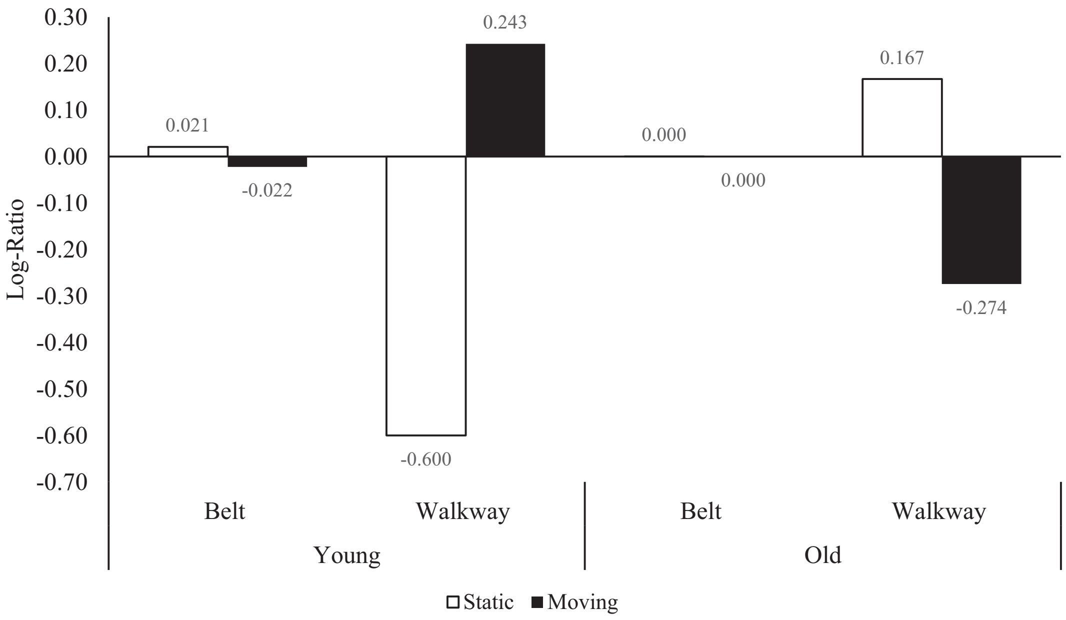

Fig. 5. Geometric means expressed in terms of a ratio measured on a logarithmic scale. The areas of interest incorporated within the isometric log ratio of Belt and Walkway areas have been plotted to allow identification of the significant interaction effect with age group.

of significant difference across perturbation magnitude measurements may be due to the relatively high standard deviations, which indicate participants used a range of behaviour adaptations to overcome environmental demands. To increase sensitivity in future studies researchers may wish to also consider measures of COM velocity or acceleration.

In extant literature, falls history is commonly utilised to classify high fall-risk participants (Ellmers et al., 2020). However, due to ethical and participant safety requirements, it was necessary that all participants in the current study declared no history of falls. MSRS 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., 2018a, 2018b). Despite this, the other older adult questionnaire results showed significantly greater FES-I and reduced ABC measures compared to younger adults. Furthermore, Bayes values (4.13 and 11.39 for FES-I and ABC respectively) supported suggestions from previous research that ABC measurements are more sensitive to fall-related anxiety in low risk older adults than FES-I (Powell and 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 and Hollands, 2007; Young and Hollands, 2012a, 2012b).

Consistent with the interpretation of self-report measures considered, and 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. A significant interaction effect revealed that older adults increased their approach times more than younger adults when accuracy was demanded. Although increased approach time may reflect participants adopting behaviours that promote certainty when negotiating challenging environments (Matthis et al., 2018), it may also reflect that older adults prioritised accuracy of foot placement more than the younger participants and therefore approached the walkway more slowly. However, 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. This adaptation adds weight to the argument suggesting that older adults utilised increased feed-forward control (through greater regulation of the step prior to a foot target) to overcome environmental demand (Barton et al., 2017; Chapman and Hollands, 2007). The interpretation of an increase in feed-forward control is further supported by 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. These adaptations point towards a prioritisation of distal information to enable feed-forward adaptive behaviour during the approach (Chapman and Hollands, 2006a, 2006b, 2007; Young and Hollands, 2012a, 2012b).

Utilising online control has been noted as more physically and cognitively demanding than feed-forward control (Ellmers et al., 2020; Ellmers and Young, 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 and Hollands, 2012a, 2012b). Consistent with Matthis et al. (2017), who noted feed-forward control enabled walkers to traverse complex terrain whilst exploiting the dynamics that underlie the energetic efficiency of human locomotion, the emergence of 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 cost (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.

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 that previous research has considered maladaptive and associated with increased fall risk for older adults, such as significantly earlier gaze transfer and increased approach times (Almarwani et al., 2016; Bhatt et al., 2005). Specifically, earlier gaze transfer has been associated with reduced step placement accuracy (Chapman and 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 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 that behaviour such as reduced gait speed (i.e. 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 may suggest that older adults found overcoming moving surfaces or surfaces with accuracy constraints more challenging than younger adults. If so, the different adaptive behaviours observed between the age groups may have been a function of the scaling between action capabilities and environmental demand (Fajen, 2005a, 2005b; Thompson and Franz, 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.

4.2. *Behaviours as a function of environmental demand*

Following the proposal of affordance-based control (Fajen, 2005a, 2005b), which stipulates behaviours are a function of environmental demand, hypothesis two predicted 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 and Day, 2005; Weerdesteyn et al., 2004). Results showed that behaviour adaptations consistent with those recognised as a '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 et al., 2017; Domínguez-Zamora and Marigold, 2019; 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 (i.e., 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 adaptations (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 and Mole, 2018; van Andel et al., 2018a, 2018b), the online and feed-forward adaptations exhibited in the moving surface conditions promoted successful locomotion for both younger and older adults (see also: Higuchi, 2013a, 2013b). Supporting this conclusion, previous research studied participants who were exposed to mechanically elicited backwards balance loss[3] 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, Table 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, the main effects for step length (Table 4) captures the disparity between the adaptive behaviours observed when participants overcame the demands of static compared to moving surfaces conditions, and conditions that do and do not demand accuracy. Consistent with cautious gait, step length was reduced for both older and younger adults when accuracy was demanded by conditions with demarcation lines, however, step length increased when stepping onto conditions with moving surfaces (Swart et al., 2020; Thomas et al., 2020). Exemplary of this observation, 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 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. AOI analysis highlighted that penultimate step viewing was greater in conditions with moving surfaces, compared to conditions with static surfaces. However, viewing the penultimate step location was not significantly different in conditions with demarcation lines compared to conditions without demarcation lines. Thus, 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 moving rather than static surfaces, but this measure was not significantly different when comparing conditions with and without demarcation lines. 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). 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

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

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 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, 2013a, 2013b). Taken together, these findings align with recent perspectives (Withagen et al., 2017; Withagen et al., 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 cost. 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. Limitations and future directions

The experimental design explored perceptual-motor behaviours as individuals stepped onto a horizontal moving surface, however, we acknowledge there are several factors, which may influence how the current findings transfer to escalator or moving walkway environments. Firstly, a flat conveyor belt was used to represent the moving surface environment. Although this enabled participants to step on to a surface which shared escalator and moving walkway characteristics, it is possible that negotiating a surface which separates vertically might require different perceptual-motor behaviours. Secondly, when stepping onto an escalator or moving walkway participants have the use of a speed synchronized handrail. It is possible the handrail provides additional support and perceptual information to help the participant step onto the moving surface. However, we were unable to recreate this aspect of the task within the laboratory environment. Both of these limitations may be overcome through subsequent research exploring pedestrian behaviours within a naturalistic setting.

The questionnaire battery used could have been strengthened by including the Berg Balance Scale (Berg et al., 1992) and substituting the MSRS (Masters et al., 2005), which has recently been recognised as potentially lacking sensitivity in comparisons of older and younger adults adaptive locomotor behaviours with the gait specific attentional profile questionnaire (Young et al., 2020). The questionnaire battery revealed differences between older and younger participant groups, however, these results also showed that the older adult group were highly functioning and consistent with physically active older adults (e.g., ABC score of >80 %; Myers et al., 1998). Future research may benefit from examining the behaviour of higher risk older adults to further understand point of interpretation offered earlier in the discussion regarding the scaling of action capabilities and adaptive perceptual-motor behaviour.

This study has highlighted several implications for future research. First, because the older adult participant group represented a low fall risk population, future work would benefit from considering how the behaviours of high fall risk older adults may differ from younger adults or low fall risk older adults when stepping onto conditions with moving surfaces and/or accuracy demands. Second, 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. Third, 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. Finally, locomotor pointing literature has examined adaptive perceptual-motor behaviours over an approach distance that is greater than two metres, with findings indicating that participants can adapt locomotor behaviours between 5 and 8 step lengths in advance of a foot target (Hildebrandt and Cañal-Bruland, 2020; van Andel et al., 2018a). In the current study, a two metre approach was selected to ensure the experimental design represented the industry regulated characteristics of moving surface environments. Future research examining perceptual-motor behaviours over greater approach distances could provide further insight into the differences between older and younger adults such as acceleration from quiet standing (Halliday et al., 1998).

6. Conclusion

To our knowledge, this is the first study to examine gaze and gait when comparing the perceptual-motor control as people step onto moving and non-moving surfaces. Using a novel, state of the art integration of eye tracking and motion capture technologies (Hunt et al., 2022), we show differences in gait and gaze behaviours when younger and older adults negotiated static and moving surfaces. Older adults transferred gaze from the walkway footstep location earlier than younger adults and viewed the walkway less than younger adults in the moving surface conditions. These adaptations indicate older adults overcame environmental demand through greater utilisation of feed-forward control. As feed-forward control has been recognised as less physically and cognitively demanding than online control (Barton et al., 2019), the emergence of these perceptual-motor adaptations in older adults may suggest that adaptive behaviours were scaled to action capabilities.

To explore the influence of environmental demand, the behaviour adaptations used to negotiate conditions with moving or static surfaces were compared to the adaptations used to negotiate conditions with or without demarcation lines. Results suggest successful locomotion was a product of synergistic online and feedforward control in all experimental conditions (Matthis et al., 2017). 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 identified between environmental conditions and age groups indicate that the adaptive behaviours utilised to overcome locomotor challenges emerge as a function of the scaling between action capabilities and environmental demand.

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Ethics approval

Approval was obtained from the University of Portsmouth ethics committee. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Consent

Informed consent was obtained from all individual participants included in the study.

Open practices and data availability statement

The datasets generated and/or analysed during the current study are available in the OSF repository [https://osf.io/uhm6e/]. None of the experiments were pre-registered.

Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose.

Data availability

I have shared a link to an OSF repository within the MS.

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