THE HORIZONTAL-VERTICAL ILLUSION ON STAIRS: OPTIMISING THE VISUAL APPEARANCE OF STAIRS TO REDUCE FALLS RISK

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Abstract

Stairs are a common location for a fall and are a significant cause of injury or accidental death in older adults. Falls on stairs can be multifactorial but often occur because of a trip. Tripping on stairs may result when step dimensions/edges are difficult to discern due to the stair appearance. Previous work has developed a stair horizontal-vertical illusion which, when placed on a step, increases the perceived riser height and stair ascent foot clearances. The illusion could help to reduce stair falls, though there are several unaddressed points which importantly could affect its intended use. 1) In its current form, the illusion may not be visually suitable for older adults, those with photosensitivity or on real world stairs. 2) The perception-action link described has not been explicitly evidenced in older adults. 3) Studies have not tested the illusion on an inconsistently taller riser which can cause a trip. 4) There is also a need to develop methods that can assess foot clearance on real world stairs. Current methods are restricted by either reduced portability of equipment, low accuracy, or complex setups limiting their use for measuring foot clearances in response to the illusion on real world stairs. To address these points, a series of studies were conducted:

Study 1 determined whether modified stair horizontal-vertical illusions (reduced number of vertical riser stripes (spatial frequency) and changes to the spacing of the vertical stripes (mark space ratio)) led to increases in perceived riser heights through a series of computer-based perception tests in young (N=42: 24 ± 3 years) and older adults (N=14: 70 ± 6 years). All stair horizontal-vertical illusion designs across each test led to significant increases in the perceived riser height in both young and older adults (12-19% increase) with no differences between age groups, suggesting the stair horizontal-vertical illusion can be modified and still cause an increase in perceived riser height.

Study 2 assessed whether increases in perceived riser height due to the modified illusions were linked to increases in stair ascent foot clearance (perception-action link) and whether this impacted other stair safety measures in sixteen older (70 ± 7 years) and fifteen young (24 ± 3 years) adults. Each stair horizontal-vertical illusion led to an increase in vertical foot clearance for young (up to 0.8cm) and older adults (up to 2.1cm) as well as increases in perceived riser height (young; 13% increase, older; 11% increase) demonstrating a perception-action link. Other stair safety measures were not adversely affected by the modified illusions.

Study 3 determined whether a modified stair horizontal-vertical illusion (70-30% mark space ratio) could ameliorate reduced foot clearances that typically occur over an inconsistently taller mid-stair riser (1cm increase in this study) and whether this impacted other stair safety measures. Foot clearance reduced over the inconsistently taller riser (0.8cm) indicating participants did not adapt to the inconsistency. Placing a modified stair horizontal-vertical

illusion onto the inconsistency increased foot clearance by 1.1cm thereby ameliorating the foot clearance reduction. The illusion also led to a safer foot overhang. The stair horizontal-vertical illusion could be a practical solution for inconsistently taller stair risers, where a rebuild is usually the only solution.

Study 4 assessed the accuracy and precision of a custom photogate setup that measures foot clearance on stairs, compared to an optoelectronic system (Vicon). The photogates showed very good accuracy when compared to Vicon (mean difference of 0.15cm) though less agreement was found in the measurement precision between the two systems (upper and lower limits of agreement 1.27cm and -1.58cm, respectively). A very strong positive correlation between the two systems was also found ($r = .83$, $n = 294$, $p<.0001$). The photogate setup could be used in the future to measure stair foot clearance in response to the illusion on stairs outside the laboratory.

This work has shown evidence for a perception-action link between increased perceived riser heights and foot clearance in older adults in response to modified stair horizontal-vertical illusions. The illusion is effective in addressing a common cause of stair falls and is a useful solution for the trip risk associated with inconsistently taller risers. The creation of a new photogate setup which has good accuracy when compared to an optoelectronic system could be used in future investigations to assess the use of the illusions on stairs or raised surfaces outside of the laboratory. Future investigations should further test the effectiveness of the illusions with older adults identified at high risk for falls and explore the feasibility of implementation in public/real world environments.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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Abbreviations

ANOVA	Analysis of variance
AP	Anterior posterior
BASES	British Association of Sport and Exercise Sciences
BCM	Broadcom
BF	Bayes factors
BIG	Biomechanics Interest Group
BSI	British Standards Institute
LogCS	Logarithm contrast sensitivity
LogMar	Logarithm visual acuity
CSV	Comma separated values
ESMAC	European Society for Movement Analysis in Adults and Children
GPIO	General purpose input output
HV	Horizontal-vertical
IBM	International Business Machines Corporation
IMU	Inertial measurement unit
ISPGR	International Society of Posture and Gait Research
LED	Light emitting diode
LJMU	Liverpool John Moores University
MD	Maryland
ML	Mediolateral
MOS	Margins of stability
NB	Nota bene
NFPA	National Fire Protection Association
NHS	National Health service
NICE	National Institute for health and care excellence
PSE	Point of subjective equality
SD	Standard deviation
SF	Spatial frequency
UK	United Kingdom
USA	United States of America
WHO	World Health Organisation

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This journey has been life changing for me in ways I sometimes struggle to describe and comprehend. From a young age I have mostly been a sport performing athlete and never in my wildest dreams would I have anticipated that I would be here writing this acknowledgment as the final words to finishing my thesis for a doctoral programme of work. Completing this thesis has been by far the hardest challenge I have faced but equally the most rewarding and has pushed me far above and beyond my own perceived limits of what can be achieved. The lessons, skills and mind set I have developed from this programme of work have been indispensable to my own professional and personal development. I am forever grateful to have been part of such a fantastic institute and Biomechanics department and I sincerely believe I could not have asked for a better post graduate research experience.

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Chapter 1: Introduction to research

1.1 The problem of falls

Falls are a significant issue and are currently ranked as the second leading cause of accidental deaths worldwide (WHO, 2018). Each year approximately 646,000 falls are reported to occur globally (WHO, 2018). Falls occur across the lifespan (NHS Digital, 2020) but are known to lead to more serious consequences in older adults, often as traumatic brain injuries (Harvey and Close, 2012), hip fractures (NICE, 2009) and the need for long term healthcare in nursing homes (Tinetti and Williams, 1997). This can lead to a fear of falling (Gagnon and Flint, 2003), loss of independence, social isolation (Hajek and Konig, 2017), avoidance of activities (Zijlstra et al., 2007) and a reduced quality of life (Hartholt et al., 2011). Falls are largely attributed to the deteriorations that accompany advanced age such as losses in vision (Lord, 2006) and decreases in musculoskeletal capacity (Cadore et al., 2013). In the United Kingdom, healthcare costs associated with falls are ~£2.3million (NICE, 2013) annually, and in the United States this figure is significantly larger at $616.5 million for fatal falls alongside $30.3 billion for non-fatal injuries (Burns, Stevens and Lee 2016). The causes of falls are multifaceted and extensive in number with over 400 specific risk factors known to cause/lead to an older adult fall (NICE, 2017). The risk of falling for an older adult is additive and therefore increases with the number of risk factors present (Iinattiniemi, Jokelainen and Luukinen, 2009). These risk factors are broadly categorised as factors to do with the individual, the environment, or individual behaviour (Ambrose, Paul and Hausdorff, 2013). Age represents the primary risk factor for an older adult (defined in this thesis as ages 60 years and above) to fall, and many individual risk factors are components of this. Examples include declines in neuromuscular function (Shimada et al., 2009), cognition (Segev-Jacubovski et al., 2011), visual function (BOptom et al., 1998; Freeman et al., 2007), and taking four or more medicines per day (Ziere et al., 2006). Behavioural risk factors include risky behaviour such as carrying loads, climbing ladders or not using mobility devices prescribed to them such as canes or walkers (Gallagher and Brunt, 1996). Environmental factors are more situational but generally include inadequate lighting conditions, clutter, slippery floors, unsecured mats/rugs, lack of non-skid surfaces (Gillespie et al., 2012) and stair design/dimensions (Jacobs, 2016).

1.2 Stair safety and falls

From 2019 to 2020, around 63% of all stair fall hospital admissions in England occurred in those aged 60 years and above (NHS Digital, 2020). Older adult falls are linked to the difficulty older adults face negotiating stairs in homes or in public (Tinetti, Speechley and Ginter, 1988; Nevitt, Cummings and Hudes, 1991; Bergland, Jarnlo and Laake, 2003). A questionnaire report shows stair negotiation to be one of the top five most difficult tasks of daily living an older adult must perform (Williamson and Fried, 1996). Stairs are a significant difficulty for older adults as they involve navigating surface level transitions that challenge an older adult’s capacity to respond to this environmental feature (Reeves et al., 2008; Samuel et al., 2011). Stairs are a common location cited in the circumstance of a fall (Jacobs, 2016; NHS Digital, 2020), often leading to accidental deaths in older adults (Startzell et al., 2000; RoSPA, 2020) and are a significant predictor for a hip fracture injury (Abolhassani et al., 2006). When compared to level walking, stairs represent a disproportionately high risk for injury and mortality (Hemenway et al., 1994; Startzell et al., 2000). Incident records show 51% of traumatic brain injuries occur from stair falls (Boyé et al., 2014) and older adults are three times more likely to sustain a moderate to severe traumatic brain injury falling on stairs when compared to level ground walking (Hwang et al., 2015). Falls on stairs are often more severe than falling on level ground, likely due to the repetitive collisions from the numerous steps.

1.3 Stair fall mechanisms

A fall on stairs is usually the result of a trip, slip or loss of balance and can occur during stair ascent and descent. Studies have focused largely on the fall mechanisms during descent as most falls happen during this direction of stair travel although around 1 in 3 falls still happen during stair ascent (Startzell et al., 2000). Trip risk on stairs can be characterised by the clearance of the foot over a step (Foster et al., 2014; Kesler et al., 2016), and will most likely occur during stair ascent. Foot clearance is calculated as the minimum distance of the foot to the step edge at the point of crossing. Low foot clearance in particular has been identified as hazardous for a trip (Hamel et al., 2005b; Foster et al., 2014). Variability in foot clearance may also indicate an inability to control the foot trajectory over a step (Hamel et al., 2005b). A slip on stairs may occur in the presence of high frictional forces during step landing and step push off (Hamel et al., 2005a; Li, Huang and Chiu, 2017) or when a large foot overhang is present (Hamel et al., 2005b). Foot overhang is characterised as the percentage of the plantar surface of the foot that is not in contact with the step during stance. A slip on stairs occurs mainly during stair descent but also during stair ascent. Loss of balance during stair negotiation can lead to a fall and can be caused by a trip or slip. Loss of balance can be characterised by margins of stability (Hof, Gazendam and Sinke, 2005). This reflects the position and velocity of a person’s extrapolated centre of mass relative to a defined base of support on the foot (Bosse et al., 2012; Novak et al., 2016). Loss of balance becomes most critical during single limb support where an individual is inherently unstable. Stair speed is often measured in addition to these stair fall mechanisms to understand their interaction. These biomechanical markers that reflect trips, slips and loss of balance (Figure 1.1) help to characterise the heightened stair fall risk in older adults.

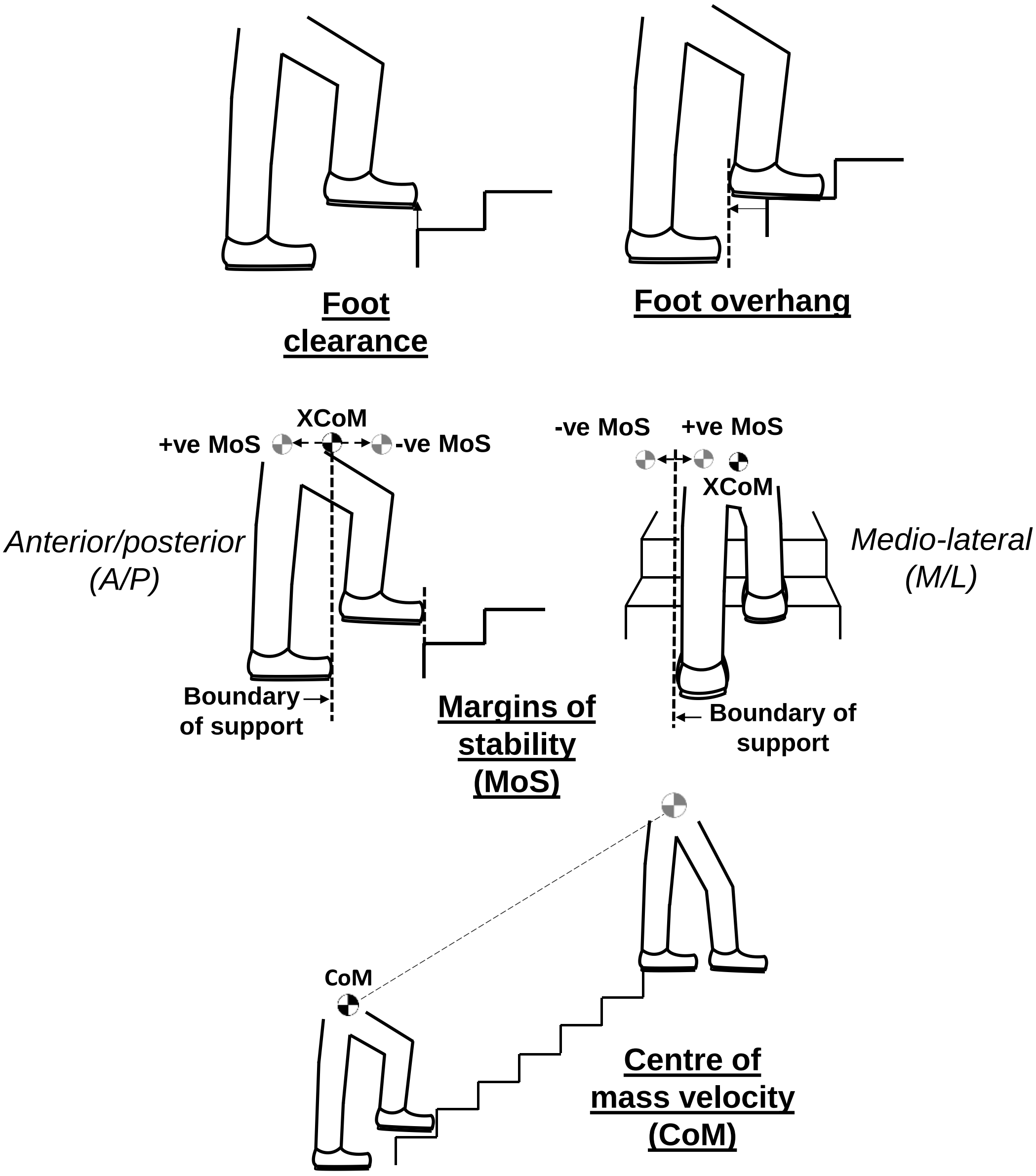


Figure 1.1 Stair fall mechanisms. Foot clearance, foot overhang and margins of stability (MoS) characterise the risk of a trip, slip or loss of balance respectively. Centre of mass (CoM) velocity characterises an individual's stair speed. XCoM = extrapolated centre of mass.

Studies that have performed age group comparisons indicate how older adult's stair behaviour differs to young adults. Older adults tend to show more variable foot clearances when compared to young adults (Hamel et al., 2005b; Ackermans et al., 2019; Thomas et al., 2020) which may indicate a reduced ability to control the foot trajectory over a step. The foot clearance magnitudes by group are unclear, with some studies showing no differences between age groups (Heasley et al., 2005; Mian et al., 2007; Francksen et al., 2020; Thomas et al., 2020), some showing reduced foot clearances (Hamel et al., 2005b; Zietz, Johannsen and Hollands, 2011; Di Giulio et al., 2020) whilst Ackermans et al. (2019) showed an increase.

These study discrepancies could be linked to the variability older adults show in foot clearance. For margins of stability, studies show opposing findings. Older adults have been found to both reduce (Bosse et al., 2012) and increase (Novak et al., 2016) anterior stability compared to young adults during stair descent, and under different lighting conditions, anterior margins of stability have been shown to be similar between young and older adults (Thomas et al., 2020). Increased margins of stability in older adults are thought to be related to slower cadence and centre of mass velocity to allow for better centre of mass control (Novak et al., 2016). Conversely, Bosse et al. (2012) reported higher centre of mass velocity as the component responsible for reduced margin of stability in older adults. Importantly, Bosse et al. (2012) used a small staircase of two steps whilst Novak et al. (2016) used a six step staircase which could explain the differences in margin of stability. The above studies do not report mediolateral margins of stability. Francksen et al. (2020) findings show older adults have reduced foot overhang compared to young adults, and older adults also show lower coefficients of friction on steps compared to young adults (Christina and Cavanagh, 2002; Hamel et al., 2005a) which are likely to reduce the risk of slipping.

1.4 Stair risk factors

General fall risk factors are categorised based upon their association to either the individual (e.g., strength and balance abilities), their behaviour (e.g., speed and technique of movement) or the environment, and this categorisation applies to the risk of falling on stairs also. Features within the stair-built environment however are more often than not cited as factors in the circumstance of a fall in the literature, (Roys, 2001; Wright and Roys, 2008; Cohen, LaRue and Cohen, 2009; Novak et al., 2016; Foster et al., 2019). For this reason, studies have explored stair environments that lead to safer stair walking responses, particularly in older adults. This has included changes to the stair dimensions, (Cesari, 2005; Wright and Roys, 2005; Bertucco and Cesari, 2009; Novak et al., 2016; King et al., 2018; Foster et al., 2019), lighting conditions (Hamel et al., 2005b; Shaheen et al., 2018; Thomas et al., 2020), stair appearance (Foster et al., 2014; Foster et al., 2015; Thomas et al., 2021), handrail design (Maki, Bartlett and Fernie, 1984; Dusenberry, Simpson and DelloRusso, 2009; Gosine, Komisar and Novak, 2021) and stair nosing (the horizontal protrusion beyond the step going) designs (Agha, Levine and Novak, 2021). Stair built environments that lead to safer stair walking behaviour include consistent stair dimensions (Francksen et al., 2020), longer stair treads (Di Giulio et al., 2020), shorter risers (Novak et al., 2016; Foster et al., 2019), handrails that are high and round (Komisar, Nirmalanathan and Novak, 2018; Gosine, Komisar and Novak, 2021) and tapered stair nosings (Agha, Levine and Novak, 2021). Stair appearances that lead to safer stair walking include well-lit stairs (Hamel et al., 2005b; Shaheen et al., 2018), using high powered LED bulbs instead of compact fluorescent bulbs (Thomas et al., 2020), the use of step edge highlighters and unambiguous stair patterns (Zietz, Johannsen and Hollands, 2011; Foster et al., 2014; Thomas et al., 2021). Such stair environments can lead to increased and more consistent foot clearances, improved centre of mass control, reduced foot overhang, and quicker/better grip of handrails to control stair walking stability.

1.5 Vision and the appearance of stairs

The appearance of stairs is very important, providing the visual information (such as perceived step dimensions) that helps inform the chosen stair action to complete the stair negotiation (Hale and Glendon, 1987; Templer, 1995). The stair appearance becomes even more critical for older adults as vision is typically reduced (impaired visual acuity and contrast sensitivity) in this age group (Lord, 2006; Freeman et al., 2007) meaning visual judgement of the stairs are likely adversely affected. For example, in a home safety program designed to reduce falls in older adults 75 years and above with visual impairment, stairs and steps/kerbs were found to be the most common environmental hazards associated with an older adult fall (30% of all hazard related falls) (La Grow et al., 2006). Impaired vision during stair ascent leads to more cautious stair behaviour characterised by improved dynamic stability, foot clearance and slower forward movement (Heasley et al., 2004; Heasley et al., 2005). Stair visual information is used in a feedforward manner, meaning information is taken approximately 2-3 steps away from the stair walker’s position (Zietz and Hollands, 2009; Den Otter, Hoogwerf and Van Der Woude, 2011; Miyasike-daSilva, Allard and McIlroy, 2011). The interpretation of this visual information then guides the stair action response, however this process can be affected by how stairs visually appear.

Stairs can often appear completely uniform (Kim and Steinfeld, 2019) or patterned (Thomas et al., 2021) which can make discerning the step edge difficult (Figure 1.2). This is problematic for tripping on stairs as the foot clearance is a response to the perceived step dimensions/step edge location (Foster et al., 2015). Stairs with such appearances can lead to dangerously low and/or variable foot clearances which can increase the risk of tripping when crossing the step. This increased risk has been demonstrated during stair descent when a step edge highlighter is pushed back (misrepresented) from the true step edge location (Foster et al., 2014). When abutting a step edge, a high contrast edge highlighter acts as a useful visual cue during stair descent to increase foot to step edge clearance and also helps to improve dynamic stability (Simoneau et al., 1991; Zietz, Johannsen and Hollands, 2011; Foster et al., 2014; Thomas et al., 2021). The evidence demonstrating the benefits of edge highlighters mean stair building regulations recommend its use (Gov, 2010) and these can often be found on public stairs. For stair ascent however, the available evidence shows that edge highlighters on steps are not as effective at increasing foot clearance (Foster et al., 2015) and no other studies formally evidence its benefit on other stair safety measures during ascent.

Figure 1.2 Examples of stairs uniform in appearance or covered in patterns that make it difficult to discern the step edge.

1.6 The stair horizontal-vertical illusion

A previously developed solution for improving stair safety during ascent is the stair horizontal-vertical (HV) illusion, which makes a step appear taller than its actual height (Figure 1.3A) and increases foot clearance over the step it is superimposed upon (Elliott et al., 2009; Foster et al., 2015). The stair illusion was created through sinewave or square wave gratings with and without an edge highlighter. With a sinewave configuration, Elliott et al. (2009) found a 0.53cm increase in the perceived riser height and ~0.5cm increase in foot clearance. Foster et al. (2015) improved the illusion by using a square wave configuration which provides better visual contrast and incorporated an edge highlighter into the design which further increases the perceived riser height. On a three-step staircase Foster et al. (2015) found ~1cm increase in foot clearance and up to a 20% increase in perceived riser height. Importantly, the illusion has not been found to adversely affect stability or other typical measures of stair safety (Foster et al., 2015) despite the mismatch of perceptual and physical information about the stair riser height. The square wave version of the stair illusion used by Foster et al. (2015) appears as black and white stripes spaced equally apart with a black step edge highlighter (strip) that abuts the tread edge. The illusion was developed on the basis of the original HV illusion (Avery and Day, 1969), whereby the vertical line in a figure T appears longer than the horizontal line despite both lines being of equal length (Figure 1.3B). This effect is thought to represent a perception-action link (Goodale and Milner, 1992), i.e., the increase in the perceived step riser height is thought to cause the increase in foot clearance. The stair HV illusion could therefore be an effective solution for improving stair safety, particularly for ascent on public stairs whilst still aiding safe stair descent due to the incorporated edge highlighter in its design; the benefits of which have been described above.

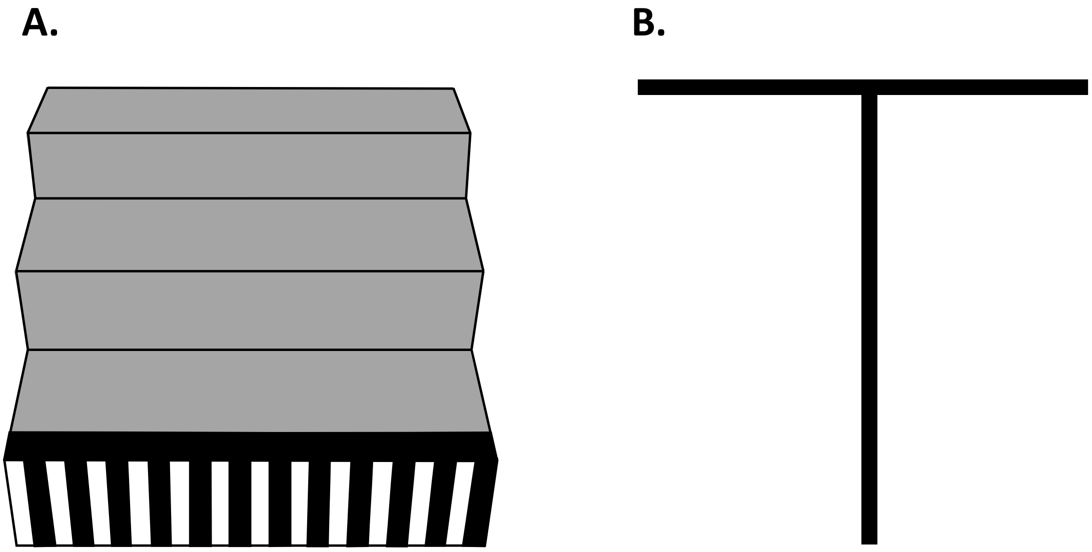


Figure 1.3 A = Stair horizontal-vertical illusion. The stair design is characterised by square wave gratings on the step riser and a top edge abutting edge highlighter positioned on the going of the step. B = The original horizontal-vertical illusion. The vertical line is perceived to be up to 20% longer than the horizontal despite both lines being of equal length.

1.7 Modifying the stair HV illusion

The stair HV illusion appears as square wave gratings at a spatial frequency of 12 cycles per metre (Figure 1.3A). For older adult vision, those with photosensitivity and for use on real world stairs, a simpler design that still leads to a stair safety benefit may be better suited as the current design could be difficult for older adults to visually interpret, potentially lead to visual stress (such as nausea and dizziness) and not be aesthetically pleasing. Foster et al. (2015) found increasing the spatial frequency resulted generally in an increase in the perceived riser height though the black and white stripes appear thinner as a result (equidistant). Thinner stripes will likely place greater demand on visual acuity and contrast sensitivity to discriminate the square wave cycles in the design, which may not be ideal for older adults due to the natural age related deterioration in visual function (Lord, 2006). The magnitude of the perceptual effect is dependent upon the spatial frequency (Foster et al., 2015), meaning the visual interpretation of these cycles has importance. The stair illusion design that is most current is characterised by a spatial frequency of twelve cycles per metre of black and white equidistant stripes with high luminance contrast. The combination of these visual properties in patterns could potentially cause visual stress in observers, and in more severe cases photosensitive epilepsy and migraines (Wilkins et al., 1984; Hermes, Kasteleijn-Nolst Trenite and Winawer, 2017), though the underlying neural mechanism for this is not well understood (Hermes, Kasteleijn-Nolst Trenite and Winawer, 2017). Importantly, Foster et al. (2015) used the twelve cycle per metre design for increasing foot clearance on stairs, but also found separate perceptual and foot clearance increases at the lowest spatial frequency tested (four cycles per metre) on a single step. This effect (perceptual and foot clearance) was reduced in magnitude when compared to the twelve-cycle design (0.05cm reduction in foot clearance) but still suggests that reduced designs can have a stair safety benefit. A design with reduced spatial frequency would also appear less complex which may be more aesthetically suitable for stairs where a minimalist appearance is preferable.

Investigating whether design modifications can be made that address the points raised regarding suitability for older adult vision, photosensitivity and aesthetics would help optimise the illusion for older adults and for placement on real world stairs. The stair HV illusion is thought to be effective through a perception-action link meaning that the increases in perceived riser height lead to an increase in foot clearance. The previous findings do indicate this link in young adults (Elliott et al., 2009) though the assessments with older adults appear incomplete as the studies using stair HV illusions do not explicitly evidence this in older adults.

1.8 Establishing a perception-action link

The stair HV illusion is suggested to work on the basis of a perception-action link. Whilst increases in foot clearance alone have been found in young and older adults in response to the illusion (Elliott et al., 2009; Foster et al., 2015), the effect of the HV illusion on perceived riser height has not yet been assessed in older adults. This is important as the two visual streams hypothesis (Goodale and Milner, 1992) suggests there are two separate neural streams in the brain for processing vision for perception (ventral stream) and vision for action (dorsal stream) (Figure 1.4). The two separate streams have limited interaction (Milner and Goodale, 2008) meaning perceptual responses may not always correspond to an action. This has been evidenced mostly through the use of the Ebbinghaus illusion, whereby a target circle appears smaller when surrounded by larger circles but appears larger when surrounded by smaller circles (Figure 1.5). Despite these perceptual changes, when the target circle is grasped, the maximum size of the grip aperture remains unchanged (Aglioti, DeSouza and Goodale, 1995; Gentilucci et al., 1996). Subsequent investigations however support no stream dissociation when methodological factors (such as how perception is quantified or the presentation of the illusion) are controlled for (Smeets and Brenner, 2006; Franz and Gegenfurtner, 2008; Kopiske et al., 2016). Other illusions (such as the Ponzo and Müller-Lyer illusion) show dissociations even when methodological factors are controlled for (Westwood, Heath and

Roy, 2000; Franz, Scharnowski and Gegenfurtner, 2005; Bruno, Bernardis and Gentilucci, 2008; Ganel, Tanzer and Goodale, 2008; Bruno and Franz, 2009; Stöttinger et al., 2010). This overall shows that it may be dependent upon the illusion and task factors as to whether perceptual responses correspond to an action. Establishing whether older adults do perceive stair risers to be taller when superimposed with a stair HV illusion and whether this is then linked to an increased foot clearance will help to determine whether this visual cue can be effective at helping to reduce older adult falls. Demonstrating a perception-action link provides greater certainty that on steps where there is an increased trip risk, the stair HV illusion will lead to a safer stepping action by cause and effect.

The previous studies have so far tested the stair HV illusion on entrance/exit stair steps where most falls are reported to occur (Startzell et al., 2000). Though more recent findings show a stair dimension inconsistency at the mid-stair region can compromise stair safety (Francksen et al., 2020) and could benefit from a visual modification such as the stair HV illusion.

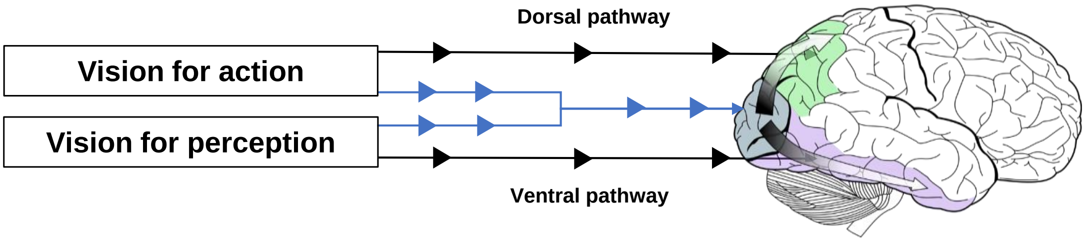


Figure 1.4 Two separate visual streams in the brain. Vision for perception (ventral pathway) and vision for action (dorsal pathway).

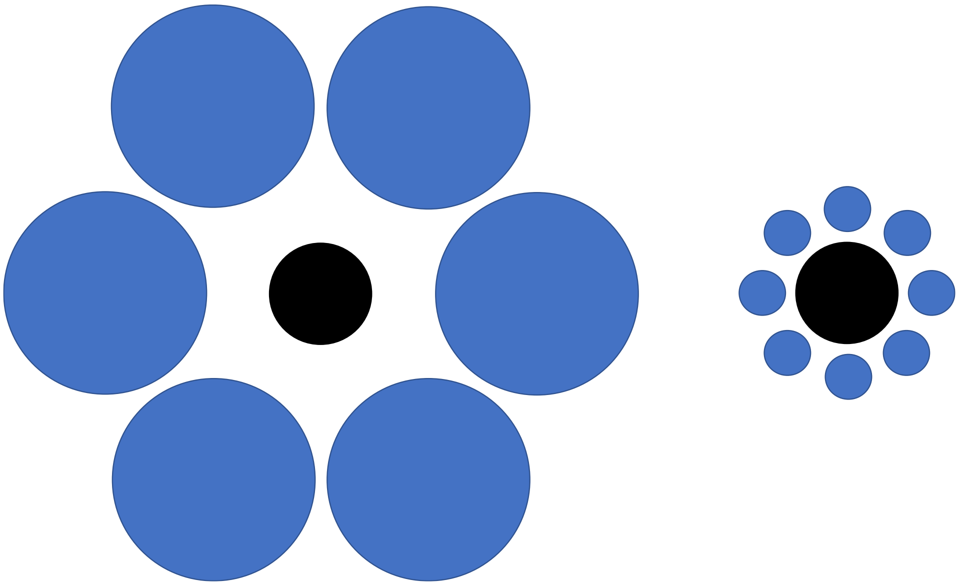


Figure 1.5 The Ebbinghaus illusion. The black target circle on the left appears smaller than the black target circle on the right due to the size of the surrounding blue circles. When attempting to grasp the target circle with the thumb and index finger, the maximum aperture of this grasp remains unchanged despite the perceptual size differences, indicating a dissociation between perception and action (Aglioti, DeSouza and Goodale, 1995). Recent findings however, suggest this might be influenced by methodological factors such as the way perception is measured (Kopiske et al., 2016).

1.9 Inconsistently taller step risers

A step that is inconsistently taller than the rest is a common and hazardous occurrence to stair safety. Whilst ergonomic reports on safe stairs have recognised this as a stair safety risk (Johnson and Pauls, 2010; Johnson and Pauls, 2012), only one study has demonstrated this recently through experimentation. Findings by Francksen et al. (2020) show foot clearance to reduce by 0.9cm over an inconsistently taller mid-stair riser (1cm increase). The riser height change is believed to go perceptually unnoticed, and the foot clearance reduction is of similar magnitude to the inconsistency. On stairs with many steps, foot clearance naturally reduces and becomes more consistent over the mid-stair portion compared to stair entrance (Simoneau et al., 1991; Foster et al., 2015; Graci et al., 2017) due to somatosensory learning of the step dimensions. The mid-stair action is more likely driven by somatosensory information than visual (Miyasike-daSilva and McIlroy, 2012; Graci et al., 2017), however the consequence of this means small changes mid-stair in step dimensions such as an inconsistently taller riser typically go unnoticed. Here a stair HV illusion could likely be a useful visual cue to offset the reduced foot clearances or at the very least add salient visual information to the step that helps to indicate the step height change. Determining whether a stair HV illusion increases foot clearance over an inconsistently taller riser is important for implementation on real world stairs as evidence suggests the prevalence of step inconsistencies in public are quite high. In an investigation of 80 stair fall reports, around 60% of the stairs had variance in riser height (Cohen, LaRue and Cohen, 2009). The stair HV illusion could be a useful solution for stairs where a rebuild to correct such inconsistencies is not always possible.

1.10 Stair HV illusions on real world stairs

To further support the stair safety benefit stair HV illusions could provide, investigations of foot clearance change in response to the illusion would be needed on stairs in a real-world setting. Such investigations will help to determine whether stair HV illusions can ultimately help towards reducing older adult falls. The typical method for assessing stair movement includes the use of optoelectronic camera systems which have accuracies within millimetres (Topley and Richards, 2020). This setup however requires multiple cameras and retroreflective markers to be placed onto participants (Figure 1.6) which significantly restrict their use for stair assessments outside a laboratory and are less suited for a measurement where ecological validity is important. Other measurement methods that are common for kinematics and have better portability are 2D cameras (Zult et al., 2019), distance sensors (Figure 1.6) (Selvaraj et al., 2018) or inertial measurement units (Benoussaad et al., 2016), though their use for measuring foot clearance is restricted by either poor measurement accuracy, signal corrections or securing instrumentation to the participant. For example, in comparison to an optoelectronic system, inertial measurement units do have quite a low average error 0.74cm when used for foot clearance measurements though these require affixing the unit to the ankle (Benoussaad et al., 2016) of an individual. Two dimensional cameras have shown an error of 4.5cm (Zult et al., 2019) when measuring foot clearance which can be interpretated as large for foot clearance measurements. The distance sensors developed by Selvaraj et al. (2018) are very precise and can measure foot clearance to a precision of 0.1cm. The sampling frequency of the sensors however are 30Hz and the sensors are not positioned at the most anterior aspect of the shoe, meaning the measurements may not reflect foot clearance at the critical instant of step edge crossing when a trip can occur. Developing an alternative method to measure stair foot clearance that circumvents these restrictions will help towards more accurately measuring the effectiveness of the stair HV illusion on real world stairs.

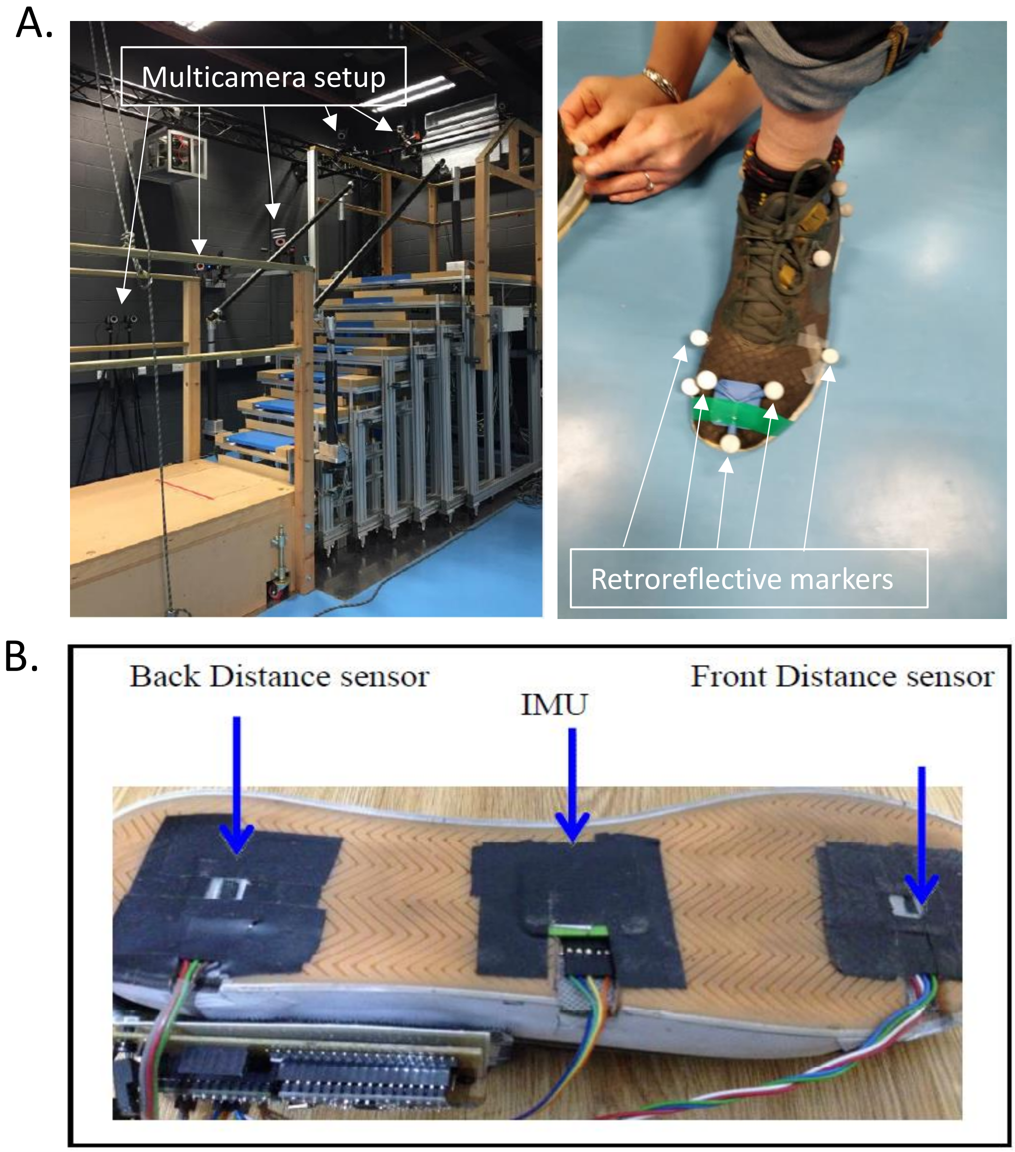


Figure 1.6 A = Example of a typical multicamera setup around a laboratory staircase and the requirement of affixing retroreflective markers to a participant. B = Distance sensors developed by (Selvaraj et al., 2018). These methods are either not very portable or require instrumentation/markers affixing to a participant. A more portable and less obtrusive measurement method would help circumvent these issues for measuring foot clearance on stairs outside a laboratory environment.

1.11 Summary

To summarise, stair falls in older adults are a significant problem that can lead to injurious or fatal consequences. The stair HV illusion could be an effective visual cue on real world stairs to help improve older adult stair safety particularly for stair ascent, but the stair HV illusion in its current form appears complex and contains features less suited to older adult vision, those with photosensitivity, and real-world stairs. Modifications that address these points will help to optimise the illusion for older adults and for placement on real world stairs. To help reduce older adult stair fall risk, it should be determined whether there is a perception action link in older adults in response to modified stair HV illusions. Determining this will help provide greater certainty that a stair HV illusion will lead to an increased foot clearance by cause and effect and an overall stair safety benefit if it were to be placed on real world stairs. Where there is also an increased trip risk over an inconsistently taller mid-stair riser, it should be established whether modified stair HV illusions can effectively increase foot clearance during stair ascent. This could provide an effective solution for such inconsistencies that pose a considerable trip hazard and would act as an alternative solution when a stair rebuild is not always possible. To help support the use of stair HV illusions on stairs, assessing foot clearance in response to the illusions on real world stairs is needed, though to achieve real-world implementation, first an alternative method that measures stair foot clearance and overcomes the restrictions of other measurement systems should be developed.

1.12 Aims

The primary aim of this thesis was to determine whether modified stair HV illusions can be used on stairs to help improve older adult stair safety. The secondary aim was to create and test an alternative method capable of measuring foot clearance on stairs outside of a laboratory environment. These aims were addressed through four experimental chapters and contained a series of objectives:

- Study 1 (Chapter 2) investigated whether modified stair HV illusions increase the perceived riser height in older and young adults.
- Study 2 (Chapter 3) determined whether there was a perception-action link between increased perceived riser heights and increased foot clearances in older and young adults and assessed whether this impacted other stair safety measures.
- Study 3 (Chapter 4) assessed whether modified stair HV illusions could ameliorate the reduced foot clearances over a mid-stair inconsistently taller riser and whether this impacted other stair safety measures.
- Study 4 (Chapter 5) determined the precision and accuracy of a custom foot clearance measurement method against an optoelectronic system.

Chapter 2: Psychophysical determination of modified stair horizontal-vertical illusions

The findings presented in this chapter have been published in Experimental Gerontology titled: **The next step in optimising the stair horizontal-vertical illusion: Does a perception-action link exist in older adults? (Skervin et al., 2021).** A copy of this publication is available online via: https://doi.org/10.1016/j.exger.2021.111309.

The findings from this chapter have been presented at the following conferences:

- LJMU Faculty of Science Research Day 2019 (awarded best oral presentation prize)
- The British Association of Sport and Exercise Sciences (BASES), Biomechanics Interest Group (BIG) 2019, (awarded best poster presentation prize) (Appendix A, Figure A.1)
- International Society of Posture and Gait Research (ISPGR 2019) (Poster presentation)
- European Society for Movement analysis in Adults and Children (ESMAC 2019) (Oral presentation)

2.1 Introduction

To clear steps safely during stair walking, perceptual judgements of step dimensions are made to inform an appropriate stepping action. For stair ascent, visual judgement of step riser heights guides how high the foot must be lifted to clear steps safely (Elliott et al., 2009; Foster et al., 2015). Previous work developed a stair horizontal-vertical illusion which increases the perceived step riser height and foot clearance (Elliott et al., 2009; Foster et al., 2015) which can be useful on stairs where trips/falls often occur due to the stair appearance (e.g. stairs that appear uniform or ambiguous). The illusion is currently characterised as square wave gratings (black and white stripes) at a spatial frequency of 12 cycles per metre. A modified design however, for the benefit of older adult vision, photosensitivity to striped patterns and use on real world stairs may be better suited. The current design could be difficult for older adults to visually interpret, potentially lead to visual stress and may not be aesthetically pleasing on real world stairs. Changes to the design spatial frequency and mark space ratio (occupying space of black to white stripes) could help to make the design more suited for these purposes but this might reduce the perceptual effect. Findings by Foster et al. (2015) show reducing the spatial frequency may reduce the perceptual effect (reduced overestimations in perceived riser height) and so far, the perceptual effect has been demonstrated only with an equal mark space ratio design. Additionally, the work by Foster et al. (2015) and Elliott et al. (2009) shows perceptual effects in young adults only meaning it is not clear whether/how older adults perceptually respond to stair HV illusions. Previous work by Schofield, Curzon-Jones and Hollands (2017) show older adults have reduced visual/perceptual sensitivity in a task based on perception of textures (due to natural vision declines), suggesting visual perception in older adults can differ to young adults.

Assessments of visual perception are typically performed through psychophysical experimentation as this allows quick and easy manipulation to features of interest in an image/test stimulus. The most common approach requires the presentation of images/stimuli on a computer screen using a two-interval forced-choice task (Prins, 2016).

2.1.1 Aim

The aim of this experimental chapter was to use psychophysical experimentation to determine whether modified versions of the stair HV illusion increased the perceived step riser height in young and older adults.

The objectives were as follows:

- Confirm the perceptual effect of the stair horizontal-vertical illusion.
- Assess whether reducing the spatial frequency changes the perceptual effect.
- Assess whether modifying the mark space ratio changes the perceptual effect.

- Determine whether older adults show differences in perceived riser heights compared to young adults in response to the modified illusions.

It was hypothesised that the stair HV illusions would increase perceived riser height and that this effect would be greater in young compared to older adults.

2.2 Method

2.2.1 Participants

Forty-two young adults and fourteen older adults (Table 2.1) were recruited from the university staff/student body and the local community and provided written informed consent to take part. Different young adults took part in the four sub-parts of this experiment (see below) and older adults only took part in the final experiment. All participants were free from any neurological condition or low vision that would prevent them from being able to visually judge the height of step risers. Presence of low vision was assessed through tests of visual acuity and contrast sensitivity using The Freiburg Visual Acuity Test (Bach, 1996). Participants were excluded if scores were higher than 0.5 LogMar (WHO, 2019) for visual acuity, and lower than 1.5 LogCS (Parede et al., 2013) for contrast sensitivity. Nonparametric statistical analysis showed young adults had better visual acuity (-0.08 ± 0.10 LogMar) than older adults (0.15 ± 0.37 LogMar) ($U = 39.5, p = .020$) and better contrast sensitivity (young: 1.95 ± 0.14, older: 1.67 ± 0.29 LogCS; $U = 25, p = .002$). Numerous tests were performed in this chapter therefore a sample size estimate was not performed. Such computer-based perception tests are often performed with small sample sizes to determine whether an effect is either present or absent (Anderson and Vingrys, 2001). This study received institutional ethical approval (18/SPS/039 08/08/2018) and conformed to the declaration of Helsinki.

Table 2.1 Participant demographics.

	Young	Older
No. of participants	42 (18 female)	14 (8 female)
Age (years)	24 ± 3 (range: 18-29)	70 ± 6 (range: 60-83)
Visual Acuity (LogMAR)	-0.08 ± 0.10*	0.15 ± 0.37
Contrast Sensitivity (LogCS)	1.95 ± 0.14*	1.67 ± 0.29

* = significant difference from a Mann-Whitney U test between young and older adults (Visual Acuity: $U = 39.5$, $p = .020$; Contrast Sensitivity: $U = 25$, $p = .002$).

2.2.2 Experimental design

A linked series of four computer-based perception tests (experiments 1A-D) were performed, using a forced choice psychophysical procedure, programmed in PsychoPy (Appendix B, Figure B.1) (Peirce et al., 2019). The stair HV illusion effect was firstly ascertained by replicating the previous design developed by Foster et al. (2015) and by comparing differences in perceptual response to arbitrary patterns (experiment 1A). Comparisons to reference steps with edge highlighters were also made to assess its contribution to the perceptual effect (experiment 1B). The assessment of modified designs included stair HV illusions with a reduced spatial frequency/number of vertical stripes (experiment 1B: representing a better visual aesthetic) and modified mark space ratios (experiment 1C: to reduce the visual stress potentially associated with the illusion). Four stair HV illusion designs from these perception tests were then chosen based on the presence of a perceptual effect, the design saliency and aesthetic and were used to assess perceptual differences between young and older adults (experiment 1D). Figure 2.1 shows the different step riser designs used and the participants for each perception test.

For each trial, participants were asked to compare an image of an outlined stair that had a fixed-height bottom riser with a stair HV illusion pattern or arbitrary design (test stimulus), to an image of a plain outlined stair (reference stimulus) that varied in bottom riser height (to control for response bias) and to then select the stair that appeared to have the taller bottom riser through a keyboard response. Each stair HV illusion was presented in its full form (vertical stripe(s) with an abutting step edge highlighter (see Figure 2.1) to maximise the perceptual effect (Foster et al., 2015)). This represented a treated step.

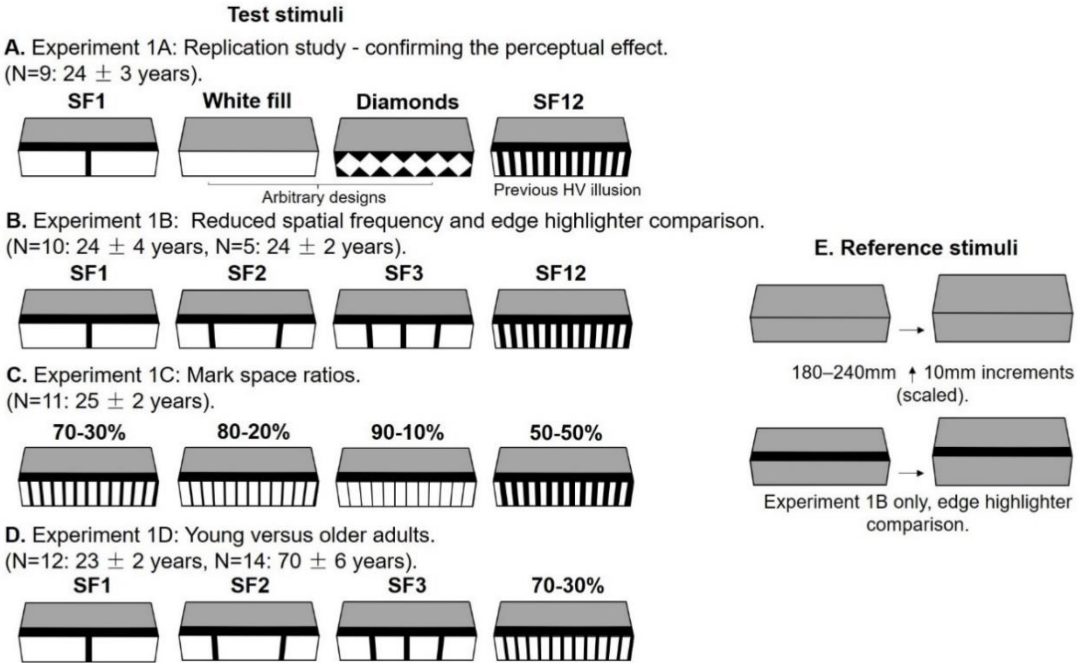


Figure 2.1. Bottom step riser designs (test stimuli) compared to plain bottom risers (reference stimuli) within each perception test. Test stimuli in experiment 1B were additionally compared to reference stimuli with edge highlighters. SF12 = previously developed stair HV illusion in young adults (Foster et al., 2015). All other stair HV illusions represent modified designs for a simpler appearance or to reduce the photosensitive trigger for the visual stress potential. Test and reference stimuli were presented over a grey background on screen, represented as grey fill on the steps. Numerical percentages represent the occupied space of white to black (mark space ratio) respectively on the riser. Young adults were used in experiments 1A-1C to preserve older adult recruitment for the age group comparison (experiment 1D). NB: SF= spatial frequency.

For experiments 1A, 1C and 1D, reference steps appeared plain to represent an untreated step and to represent how stairs would typically appear in the real world. For experiment 1B reference steps included an edge highlighter to assess the perceptual effect when the presence of edge highlighters were matched. Each stair appeared in succession on screen for 500ms in a randomised order with a 1000ms interval between the two stimuli in each trial (Figure 2.2).

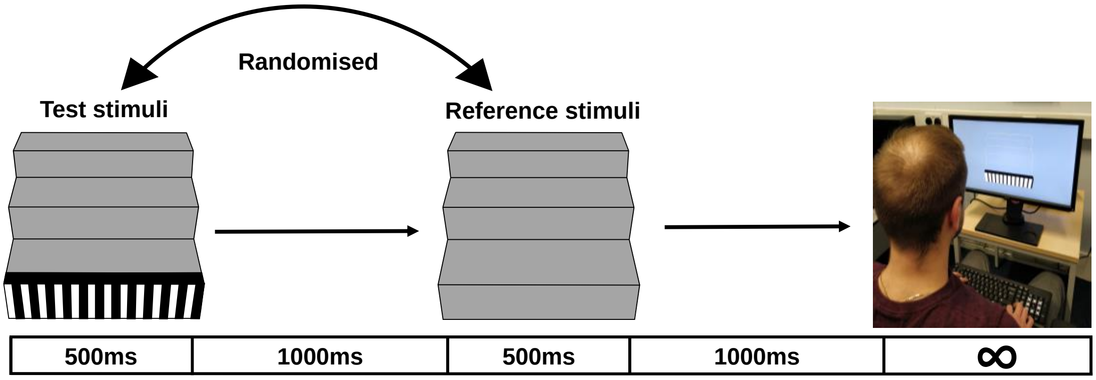


Figure 2.2. Trial procedure for each experiment. One of four test steps were compared to one of seven reference steps. Participants then selected the stair image that appeared to have the taller bottom step through a keyboard response.

Each perception test followed this trial procedure and contained four different test stimuli and seven reference stimuli which represented scaled riser heights found on physical stairs (test stimuli = 190mm, reference stimuli = 180 to 240mm in 10mm increments). Participants were positioned 33cm away from the monitor at a perpendicular eye level to the computer screen (BenQ XL2430 -B) to represent the viewing of physical steps from a distance of 1.4m away at an eye height of 1.6m (approximating that of an average older adult height; Elliott et al. (2015)). For all participants in experiments 1A-1C and the first five older adults in experiment 1D, 560 responses were initially obtained over four equal sittings of 140 trials. For each sitting, test stimuli were compared to each reference stimuli five times totalling 20 comparisons at each reference stimuli level across all sittings. Combinations of test and reference stimuli were randomised across trials such that all combinations appeared equally often. The order in which the test and reference stimuli were presented within each trial were also randomised. Statistical analysis (One-way Repeated Measures ANOVA: α=.05) revealed no differences in perceived riser heights between sittings for each experiment (*p*>.05), therefore the remaining participants in experiment 1D were instead asked to complete a minimum of one sitting but to then complete more if they were happy to do so. Data were recorded as binary responses (1 = test stimuli taller, 0 = reference stimuli taller) and were exported as CSV files.

2.2.3 Statistical analysis

A logistic function was fitted to the test stimuli taller responses plotted against the reference stimuli heights to estimate the perceived riser height of each test stimulus (Figure 2.3). Perceived riser height/point of subjective equality (PSE) was established as the point at which the test stimuli was judged taller on 50% of the trials. A One-way Repeated Measures ANOVA (α=.05) was used to compare perceived riser heights between test stimuli (experiment 1A-1C).

A Two-way Repeated Measures ANOVA (α=.05) was used to compare perceived riser heights between test stimuli and age groups (experiment 1D). Following ANOVA testing, Bayes Factors were computed for experiment 1D to determine whether non-significance in perceived riser heights between test stimuli as well as age group were driven by similarities. A Bayesian Two Way Repeated Measures ANOVA using JASP with default priors (JASP Team (2020). JASP (Version 0.14.1) [Windows 10]) was performed with test stimuli and age group as factors. Bayes Factors (expressed as BF_{01}) are reported showing the probability of the data given the null hypothesis relative to the alternative. Lee and Wagenmakers classification scheme indicating levels of evidence was used for Bayes Factor interpretation (Quintana and Williams, 2018). Residual plots were used to visually inspect all variables for normality. Data sphericity was assessed using Mauchly's test of Sphericity. When data violated the estimate of sphericity, a Greenhouse-Geisser (<0.75) or Huynh-Feldt (>0.75) epsilon correction was used. Significant main effects were followed with post-hoc tests using a Bonferroni correction for multiple comparisons. In the presence of non-significance between test stimuli, data were pooled across test stimuli and a One Sample t-test was used to compare the pooled perceived riser heights to the veridical riser height. For comparisons with repeated One Sample t-tests, the alpha level was divided by the number of comparisons (experiment 1A α=.013; experiment 1B-1D α=.05). All frequentist statistical analyses were performed in SPSS 26 (SPSS version 26.0 IBM Corp, 2019).

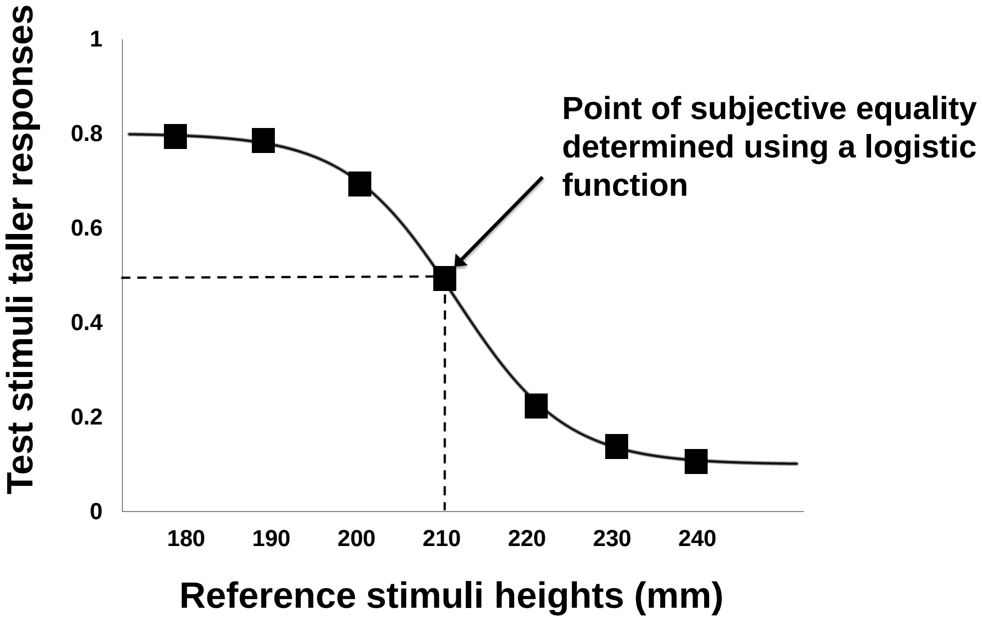


Figure 2.3. Exemplar plot of test stimuli taller responses and a logistic function fit. Perceived test stimuli height was determined as the point at which the test stimulus was selected for 50% of trials.

2.3 Results

2.3.1 Experiment 1A: Replication study - confirming the perceptual effect

There was a significant main effect of test stimulus on perceived riser height ($F_{(1.214, 9.711)}$=34.218, *p<.001*, n^2_p=.811) (Figure 2.4). SF1 and SF12 were perceived to be significantly taller than White fill (SF1=13%, *p*=.003; SF12=13%, *p*=.006) and Diamonds (SF1=18%, *p*=.001; SF12=18%, *p*=.002). White fill was perceived to be taller than Diamonds (*p*=.005). SF1 and SF12 led to significant overestimations in perceived riser height (19% increase from veridical riser height; *p<.001)*. White fill was perceived to be taller than the veridical height (*p*=.001). No significant differences in perceived riser height were found between Diamonds and the veridical riser height (*p*=.505).

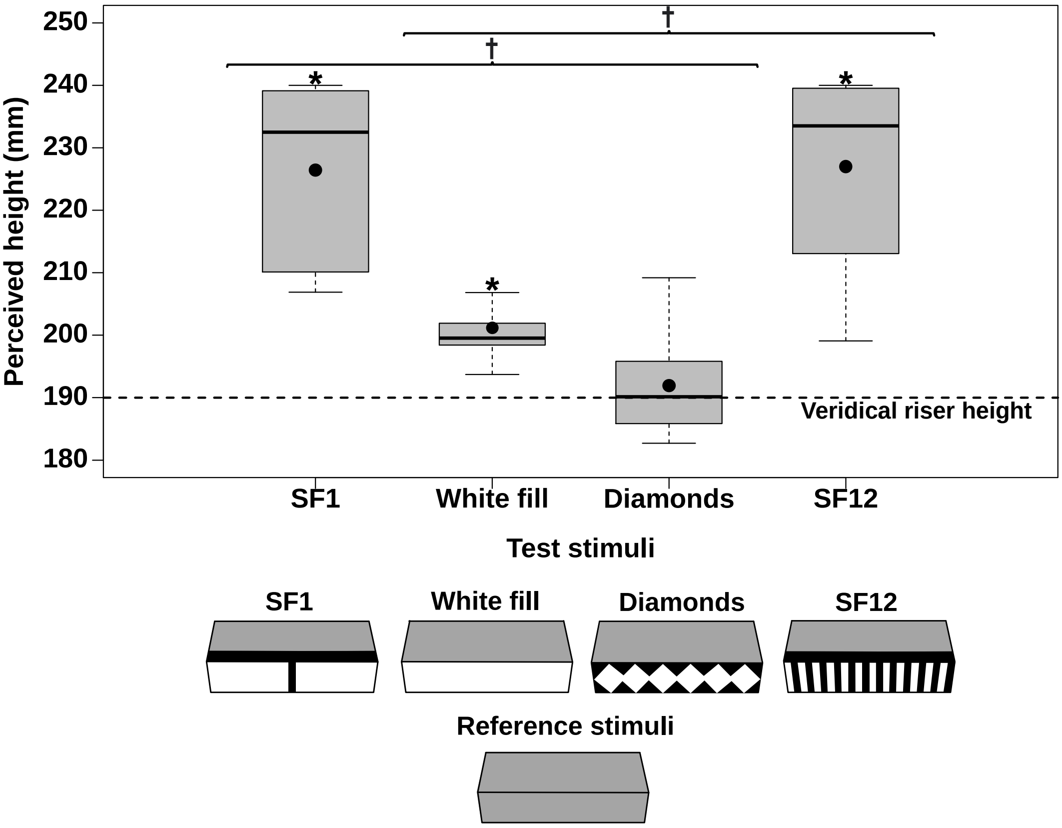


*Figure 2.4. Replication study - confirming the perceptual effect. Each of the stair HV illusion designs led to a significant increase in the perceived riser height. Box plots present the mean (●) and median (–). * = Significant increase from the veridical riser height. † = significant difference between test stimuli.*

2.3.2 Experiment 1B: Reduced spatial frequency and edge highlighter comparison

No significant differences were found between each test stimulus for perceived riser height when compared to the plain reference stimulus ($F_{(3,\ 27)}=1.672$, $p=.196$, $n^2_p=.157$) and plain reference stimulus with an edge highlighter ($F_{(3,\ 12)}=1.741$, $p=.212$, $n^2_p=.303$). All spatial frequencies (SF1, SF2, SF3 and SF12) caused significant increases in the perceived riser heights when compared to the veridical riser height (Figure 2.5). However, the increases in perceived riser height were bigger when the test stimuli were compared to the plain stimulus with no edge highlighter (15-17% increase; $p<.001$), compared to the plain stimulus with an edge highlighter (6-9% increase; $p=.024$).

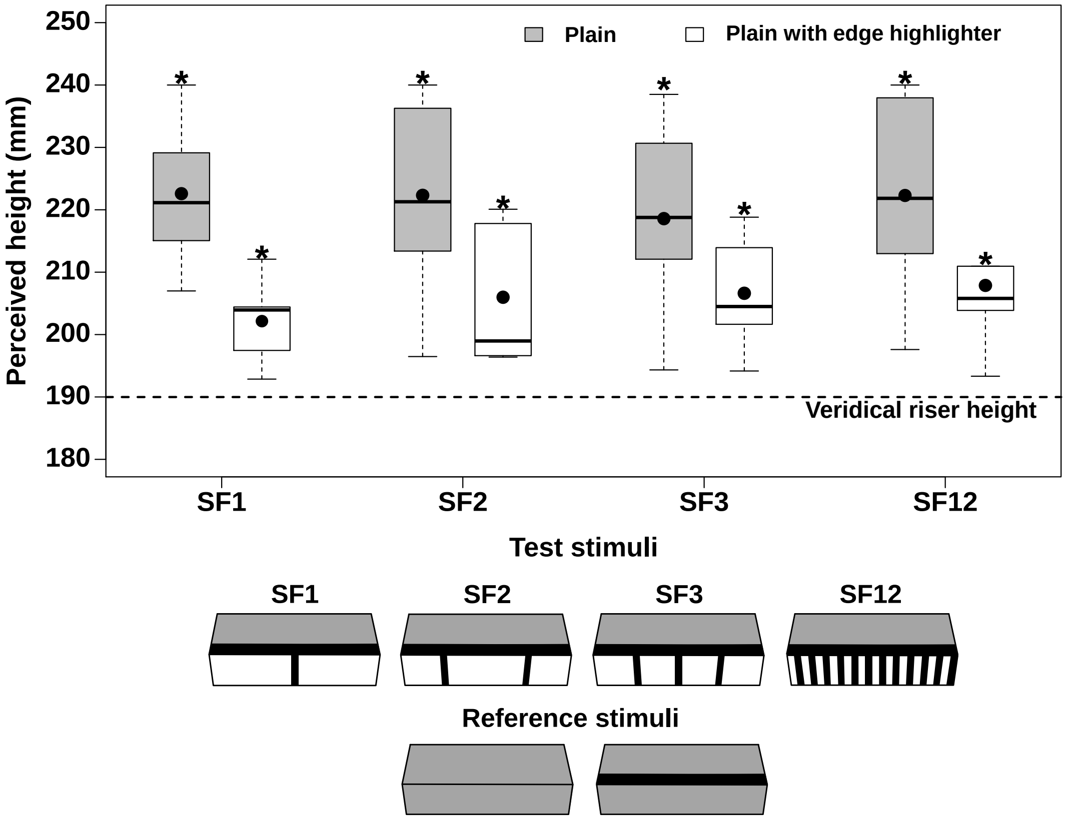


*Figure 2.5. Reduced spatial frequency and edge highlighter comparison. Each of the stair HV illusion designs led to a significant increase in the perceived riser height. Box plots present the mean (●) and median (–). * = Significant increase from the veridical riser height.*

2.3.3 Experiment 1C: Mark space ratios

No significant differences in perceived riser height were found between each test stimulus ($F_{(1.813, 18.127)}$=.734, p=.481, $n^2{}_p$=.068). All mark-space ratios led to a significant increase in the perceived riser height when compared to the veridical riser height (16-18% increase; p<.001) (Figure 2.6).

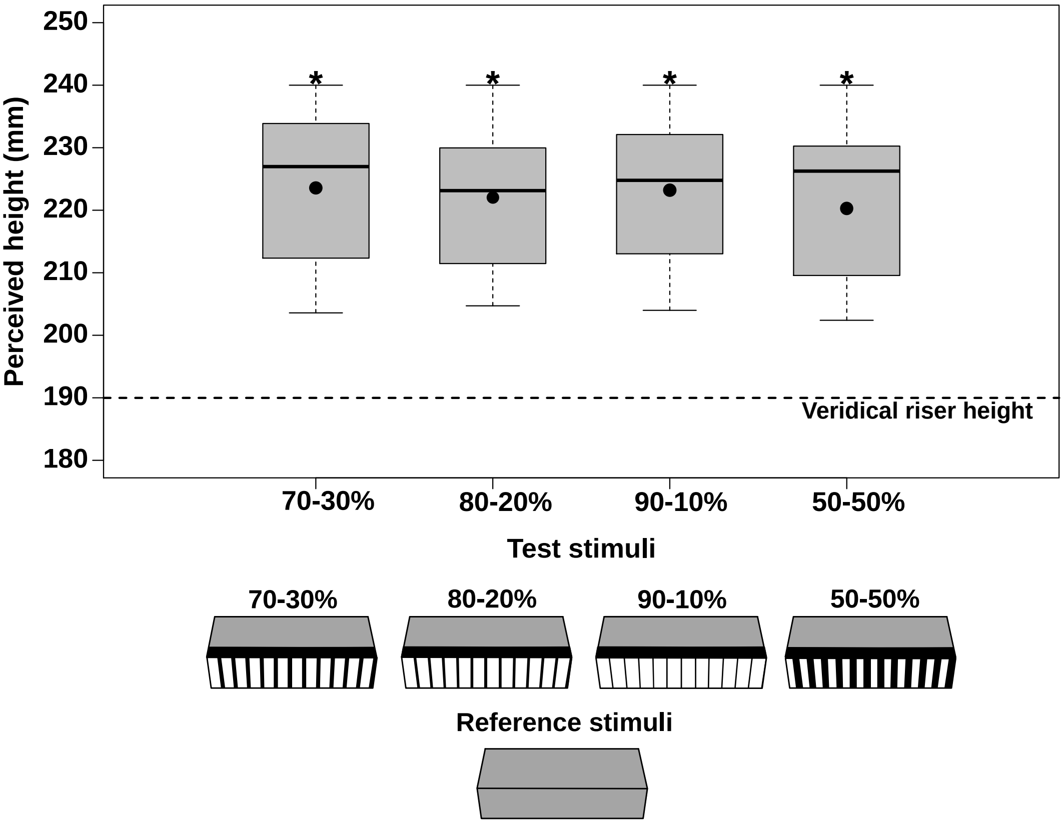


*Figure 2.6. Mark space ratios. Each of the stair HV illusion designs led to a significant increase in the perceived riser height. Box plots present the mean (●) and median (–). * = Significant increase from the veridical riser height.*

2.3.4 Experiment 1D: Young versus older adults

There were no interaction effects of test stimuli and age group ($F_{(3, 72)}$=.829, *p*=.482, n^2_p=.033). No main effects were found for test stimuli ($F_{(3, 72)}$=.921, *p*=.435, n^2_p=.037) or for age group ($F_{(1, 24)}$=1.455, *p*=.239, n^2_p=.057). When compared to the veridical riser height, the pooled test stimuli led to a significant increase in the perceived riser height (12-15% increase; *p<.001*) (Figure 2.7). Further investigation into the lack of main and interaction effects for test stimuli and age group using Bayesian inference showed the effect of age group and test stimuli to be 1.3 (BF_{01}= 1.349) and 6.3 (BF_{01}= 6.386) times more likely under the null hypothesis, representing anecdotal and moderate evidence respectively. The age group and test stimuli interaction was 4.9 times more likely under the null hypothesis (BF_{01}= 4.981), representing moderate evidence.

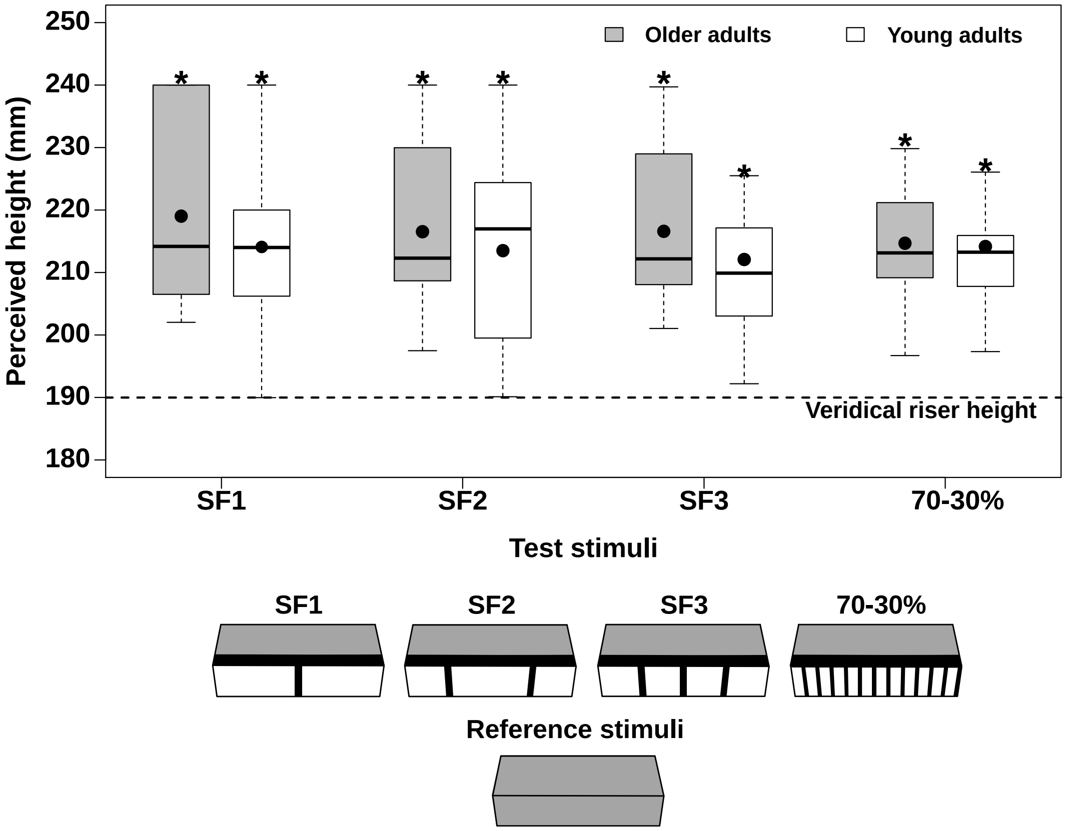


*Figure 2.7. Young versus older adults. Each of the HV illusion designs led to a significant increase in the perceived riser height. Box plots present the mean (●) and median (–). * = Significant increase from the veridical riser height.*

2.4 Discussion

The main aim of this experimental chapter was to assess whether modified versions of the stair HV illusion increased perceived riser heights and whether they were effective with older adults. We hypothesised that the stair HV illusions would increase perceived riser heights in both young and older adults, but to a greater extent in young adults. The results show that modified versions of the stair HV illusion led to increases in the perceived riser height in both young and older adults with no difference between age groups. Bayes Factors analysis suggested there was limited evidence that this lack of difference finding between young and older adults was driven by similarity. Our hypothesis is therefore partly supported.

The increased perceived riser heights with the stair HV illusions compared to the arbitrary designs in experiment 1A suggests the overestimations were due to the configuration of the stair HV illusion (i.e. the presence of vertical stripes with an abutting top edge highlighter). This is also strengthened by our stair HV illusion comparison to an edge highlighter reference stimulus (experiment 1B), whereby a reduced but significant increase in the perceived riser height was still observed. Reduced overestimations suggest the overall stair HV illusion effect is partly due to the edge highlighter which is consistent with Foster et al. (2015) who showed that edge highlighters present with vertical riser gratings reinforces the stair HV illusion, producing the greatest magnitude of riser height overestimation. Whilst edge highlighters are placed on a step going to delineate the step edge (Foster et al., 2014), the stair HV illusions here contain vertical black stripes on the riser which merge into the edge highlighter on the step going. This might have given the perception that the edge highlighter was an extension of the vertical stripes on the riser aspect of the step, thereby contributing to the increase in perceived riser height. Though equally, the white fill in the illusion design on the riser does not merge with the edge highlighter and alternatively may demarcate the vertical riser aspect from the edge highlighter. The magnitude of overestimations found in this study are also similar to Foster et al. (2015) findings. These authors reported magnitudes of ~20% for stair HV illusion designs with spatial frequencies of 4 through to 20 cycles per metre. Interestingly, the White fill arbitrary pattern we tested in experiment 1A also elicited a perceptual effect as this was perceived to be significantly taller than the veridical height. A similar effect was reported by Rhea, Rietdyk and Haddad (2010) where a full obstacle was perceived to be taller than a perimeter obstacle. This is akin to our step comparisons whereby our reference stimuli unknowingly also represented the perimeter of a step and our White fill represented a full step.

Experiment 1B showed similar overestimation magnitudes across all spatial frequencies whereas Foster et al. (2015) showed a general pattern for larger overestimations as the spatial frequency increased. This discrepancy may have resulted due to the vertical stripe widths. Foster et al. (2015) used an equidistant grating configuration for each stair HV illusion design meaning their lowest spatial frequency configuration (four cycles) had wider vertical stripes on the riser. Our lower spatial frequency configurations (SF1, SF2 and SF3) had black vertical stripe widths equal to SF12, suggesting the overall perceptual effect is partly due to the stripe width. Other perception work shows rectangles of the same height are perceived taller when narrower and shorter when wider (Beck, Emanuele and Savazzi, 2013). This effect may have been present here with the riser stripes (viewed as rectangles). There may however be an upper ceiling effect with how much the stripe width contributes to the overall effect, as we did not find differences between our mark space ratios which represented a stripe width manipulation at the same spatial frequency. A significant perceptual effect with as few as one black riser stripe fulfils part of the aim in developing a design with reduced features which may be more aesthetically suitable for public use. The mark space ratio findings in experiment 1C also show that the stair HV illusion design used previously (Foster et al., 2015) can be adapted to be more acceptable to those with visual stress and photosensitivity whilst retaining the perceptual effect at the same spatial frequency. High luminance contrast and equal mark-space widths are contributing factors in photosensitivity (Hermes, Kasteleijn-Nolst Trenite and Winawer, 2017). Importantly, the mark space ratio adjustments we used in experiment 1C reduces the luminance contrast of the stair HV illusion design. For experiment 1D, the stair HV illusions led to significant increases in riser height estimation across all designs. Furthermore, the lack of significant difference between age groups, despite significant differences in visual function, suggests the configurations of each stair HV illusion design are sufficient to elicit a perceptual effect in older adults despite the design reductions and modifications made.

2.5 Conclusion

Overall, this experimental chapter established that modified stair HV illusion designs effectively increased perceived riser height, and that older adults perceptually respond to these illusions, in a similar way to younger adults. It is not known at this point whether there is an explicit perception action link in older adults in response to stair HV illusions, or whether young and older adults respond to the modified versions of the stair HV illusion when walking up stairs.

Chapter 3: Stair analysis of foot clearance and perceived riser heights in response to modified stair HV illusions

The findings presented in this chapter were published in Experimental Gerontology titled: **The next step in optimising the stair horizontal-vertical illusion: Does a perception-action link exist in older adults? (Skervin et al., 2021)** (Appendix C, Figure C.1)**.** A copy of this publication is available online via: https://doi.org/10.1016/j.exger.2021.111309.

3.1 Introduction

The previous chapter was able to establish that older adults perceive steps superimposed with modified stair HV illusions to be taller than their actual height. For the modified stair HV illusions to provide a stair safety benefit, it is important that the modified stair HV illusions lead to increased foot clearances over the step superimposed and that this is linked to the increase in perceived riser height.

The stair HV illusion has been suggested to work on the basis of a perception-action link by previous studies. The findings by Elliott et al. (2009) demonstrate a perception-action link in young adults (increased perceived riser height leading to increased foot clearance) using a sinewave stair horizontal-vertical illusion on a single step. However, a perception-action link in response to a stair horizontal-vertical illusion has not been formally evidenced in older adults. This is important to establish as the two visual streams hypothesis (Goodale and Milner, 1992) suggests two separate visual pathways in the brain for processing vision for perception (ventral stream) and vision for action (dorsal stream), meaning perceptual responses do not always correspond to an action (Aglioti, DeSouza and Goodale, 1995). For the modified stair HV illusions to be effective with older adults it should be determined whether the increases in perceived riser heights are then linked to an increased foot clearance, indicating a perception-action link. Testing the link is particularly important as previous work has shown older adults to not adapt their foot clearance to a step perceived to be taller (Schofield, Curzon-Jones and Hollands, 2017). Superimposing a stair HV illusion onto a step may cause the perceptual information about the step riser height to differ from the physical riser height. This mismatch of information about the step could affect other important stair safety measures such as stability.

It is also not currently known whether ascending a staircase with many steps, or repeatedly ascending the same staircase, with a stair HV illusion present attenuates the effect of the illusion. Rhea, Rietdyk and Haddad (2010) found foot clearances initially increase in an obstacle crossing task due to the perceived obstacle size, but over repeated trials, foot clearance height reduces likely due to somatosensory feedback. The effect of the stair HV illusion could be lost following repeated physical foot contact on steps providing additional feedback about the step height (Chapman et al., 2010) in addition to the positional feedback from the raising of the lead limb. Findings demonstrating the effect of the stair HV illusion are from single raised surfaces or a three-step staircase (Elliott et al., 2009; Foster et al., 2015), meaning the evidence is supported for a limited number of steps only and not entirely for the top step on stairs with more than three steps. This is important as stair falls most commonly occur on the transitional steps of stairs (first and last) (Startzell et al., 2000). If an effect still exists on stairs with several more steps, an understanding of whether this is linked to a corresponding step riser height perception should be explored to determine whether this adaptation occurred independently of perceptual information. This information will help to establish the conditions with which the stair HV illusion will be most effective on stairs.

3.1.1 Aim

The primary aim of this study was to determine whether a perception-action link between increased perceived step-riser height and foot clearance exists in older adults and to secondly determine whether modified versions of the stair HV illusion elicit effects suitable to enhance stepping safety. We hypothesised that young and older adults would show increases in perceived riser height and foot clearance in response to the modified stair HV illusions and that this effect would be greater in young compared to older adults.

The objectives for this study were as follows:

- Determine whether the modified stair HV illusion increases perceived riser height and foot clearance over the superimposed steps.
- Establish whether any changes to perceived riser height and foot clearance impact stair safety.
- Assess whether the modified stair HV illusion increases foot clearance over the last step on stairs with more steps than previously tested.
- Assess whether the perceptual effect changes after repeated stepping exposure to modified stair HV illusions.

3.2 Method

3.2.1 Participants

Fifteen young adults and sixteen older adults (Table 3.1) were recruited from the University staff/student body and the local community and provided written informed consent to participate. A power analysis based on previous data (Foster et al., 2015) for the detection of a meaningful change in vertical toe clearance over a step edge, in response to a previous version of the stair HV illusion showed 14 participants were required (mean difference= 1.6, $\sigma = 1.95$, $\alpha = 0.05$, power = 80%). All participants were free from any neurological, physical condition or low vision that would prevent them from being able to visually judge the height of step risers or negotiate stairs. Presence of low vision was assessed through tests of visual acuity and contrast sensitivity using The Freiburg Visual Acuity Test (Bach, 1996). Participants were excluded if scores were higher than 0.5 LogMar (WHO, 2019) for visual acuity, and lower than 1.5 LogCS (Parede et al., 2013) for contrast sensitivity. This study was approved by the institutional research ethics committee (17/SPS/002) and conformed to the Declaration of Helsinki.

Table 3.1. Participant demographics.

	Young	Older
No. of participants	15 (10 female)	16 (7 female)
Age (years)	24 ± 3 (range: 20-30)	70 ± 7 (range: 60-84)
Height (m)	1.62 ± 0.43	1.66 ± 0.84
Mass (kg)	69.69 ± 11.80	68.49 ± 16.46
Visual Acuity (LogMAR)	-0.06 ± 0.30*	0.13 ± 0.17
Contrast Sensitivity (LogCS)	1.83 ± 0.24	1.70 ± 0.24

** = significant difference from a Mann-Whitney U test comparing visual acuity between young and older adults (U = 33, p<.001).*

3.2.2 Experimental design

To determine i) how changes in perceived riser height link to changes in foot clearance, and ii) whether repeated stepping interactions with the modified stair HV illusion on physical stairs led to changes in perception, participants completed the previously described psychophysical experiment in chapter 2 (experiment 1D) before and following the stair ascent assessment.

Participants were asked to ascend a seven-step custom-built instrumented staircase at a self-selected speed under five different stair visual conditions. Each modified stair HV illusion design (SF1, SF2, SF3, 70-30%) from the previous experiment 1D in Chapter 2 (Figure 2.1; 70-30% design referred to as SF12 for this chapter) represented an individual condition alongside a plain condition (control). These designs were selected based upon the presence of a perceptual effect in older adults from experiment 1D. Figure 3.1 shows examples of how the modified stair HV illusions appeared on the staircase. Three successful ascent trials were collected for each visual condition (totalling fifteen trials) which were performed consecutively as a block and randomised for each participant. For each block condition, the modified stair HV illusion design was superimposed onto the first and last step as these represent transitional steps where most trips/falls occur (Startzell et al., 2000). Participants began each trial approximately two/three steps away from the staircase from the same fixed position. Participants were instructed to cross the first step with the same self-selected foot for each trial, ascend the stairs in a step overstep manner and continue walking to the end of the top landing after crossing the last step. Participants were free to use the handrails if preferred. Following the completion of a trial, participants were asked to walk back down the stairs to the starting position and to step over one or two low-height obstacles placed on the starting walkway to disrupt any potential somatosensory interference from the stair descent (Foster et al., 2015). When changing visual condition, participants were instructed to look away from the staircase to minimise out-of-trial visuomotor planning. When on the stairs, participants were secured into an overhead safety harness operated by a trained belayer positioned adjacent to the staircase. Participants were asked to wear tight fitted clothing, flat soled shoes and were familiarised with the testing protocol prior to data collection. Rest periods between trials were offered throughout and the data collection took place in a single session lasting two hours.

For visual consistency, the laboratory staircase was covered with a commercially available grey covering to create a uniform appearance. Each step had a riser height of 20cm and a going length of 25cm which falls within current stair building regulations (Gov, 2010). Each of the modified stair HV illusion designs were paper printed in a matte finish, cut to size and reinforced with card. A black 5.5cm edge highlighter (size conforming to building regulations) was placed onto the going above the riser abutted to the step edge to complete each modified stair HV illusion design (Foster et al., 2014; Foster et al., 2015). All other steps (steps 2-6) remained plain with the grey covering.

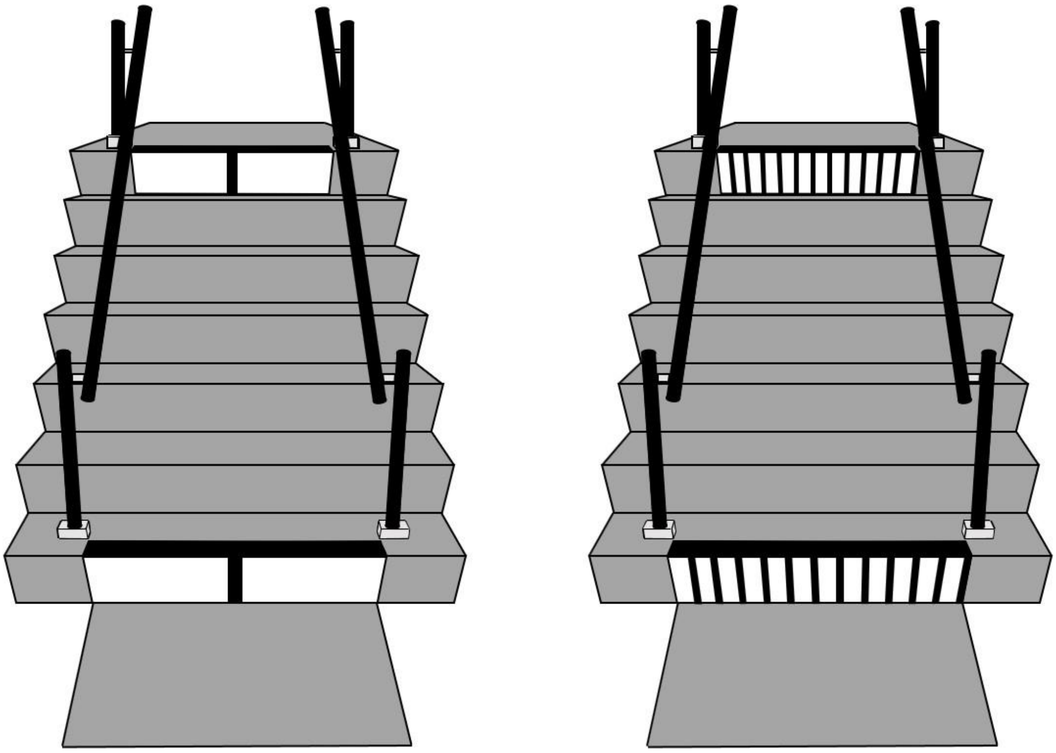


Figure 3.1 Examples of the modified stair HV illusions (SF1 and SF12) superimposed onto the first and last step of a seven-step staircase with handrails.

3.2.3 Data collection

A 26-camera motion capture system (Vicon MX, Oxford Metrics, UK) captured whole body kinematics at 120 Hz. The conventional Plug-in Gait marker set was used to model whole body kinematics with additional markers and clusters placed on the head and lower limbs for marker redundancy and to avoid occlusion from stair apparatus. A static calibration (anatomical pose) was captured to acquire whole body marker coordinates. A digitising wand (C-Motion, Germantown, MD, USA) was used to create virtual landmarks on the toe and heel-tips of participants' shoes in a separate dedicated capture. Toe-tip landmarks were created on the most anterior, inferior aspect of the shoe, heel-tip landmarks were created at the most posterior, inferior aspect of the shoe. The digitising wand was also used to create virtual landmarks that defined the location of each individual step edge on the staircase.

Previous video analysis indicates one of the differences between fallers and non-fallers results from insufficient visual scanning of stairs (Templer, 1995). Gaze duration was therefore measured using a mobile binocular eye tracker (Pupil Labs Core, Pupil Labs, Berlin) to assess whether the presence of the modified stair HV illusions on steps attract greater visual attention. The eye tracker cameras were adjusted, calibrated, and validated for each participant prior to stair ascent trials and captured gaze activity at 120Hz. No eye tracking was used with participants wearing contact lenses or glasses to avoid potential distortion of the pupil image captured from the eye cameras.

3.2.4 Data processing & analysis

All marker data were labelled, and gap filled in Vicon (Vicon Nexus 2.6, Oxford Metrics), and exported as c3d files for analysis using Visual 3D (C-Motion, Germantown, MD, USA). Raw gaze data were filtered with the Pupil Labs offline fixation detector (2° maximum dispersion angle, 60ms minimum duration) and then subsequently analysed in Pupil Player software. Step fixations were defined as continuous gaze for a minimum of two video frames on either the riser or going of the step. Gaze was considered to be directed onto a step when half of the gaze circle was overlapping a step.

Marker data were filtered using a fourth order Butterworth bidirectional filter (cut-off frequency 6Hz). In addition to lead vertical foot clearance, other measurements included margins of stability (MOS) in the anterior-posterior (AP) and mediolateral (ML) directions, foot overhang and stair speed. These measures determined whether the mismatch of information from the perceived riser height and the actual riser height from the modified stair HV illusions disrupted normal dynamic stability and stepping characteristics. Outcome measures were calculated on each of the seven steps. Lead vertical foot clearance, defined as the vertical distance of the virtual toe tip landmark to the step edge was extracted at the point where the difference in AP position between the step edge and virtual toe tip landmark was zero. Vertical foot clearance was computed as opposed to the minimum resultant foot clearance to allow a trip risk measurement at the point at which a trip usually occurs which is at step edge crossing. This is also the point at which all previous research has evidenced the illusion's foot clearance effect (Elliott et al., 2009; Foster et al., 2015; Foster et al., 2016) and may help when comparing the illusion design effects between studies. Whole body centre of mass (CoM) was generated as a link model-based item in Visual 3D. Stair speed was calculated as the first derivative of the CoM AP trajectory from the start of the trial to initial contact on the top landing of the trailing foot. MOS were calculated and defined in the AP direction as the distance between the extrapolated CoM (*xCoM*) and the virtual toe tip landmark and in the ML direction as the distance between the *xCoM* and 5th Metatarsal head (Hof, Gazendam and Sinke, 2005; Bosse et al., 2012; Novak et al., 2016).

xCoM was defined as:

$$xCoM = pCoM + vCoM/\sqrt{(gl^{-1})}$$

where *pCoM* is the AP/ML position of the CoM, *vCoM* is the instantaneous AP/ML velocity of the CoM, g is acceleration due to gravity, and *l* is the absolute distance between the CoM and the ankle joint centre.

MOS were calculated at the point of lead vertical foot clearance over each step which represents the most hazardous point for a trip. Foot overhang was defined as the distance between the virtual heel tip landmark and the virtual step edge location(s), calculated as a percentage of foot length. Gaze duration was calculated for each step as percentages of the trial summed fixation duration. Due to technical issues with tracking of the pupil during the stair movement (for example, gaze being directed below the cameras), gaze data for young adults was discarded and data from six older adults were excluded from analysis.

3.2.5 Statistical analysis

A Two Way Mixed ANOVA compared kinematic variables for within-subject effects of visual condition (x5: plain, SF1, SF2, SF3, SF12), between-subject effects of age group (x2: young and older adult) and interactions between visual condition and age group. For gaze data, a One Way Repeated Measures ANOVA compared total step gaze durations for older adults within-subject effects of visual condition. Separate ANOVAs were performed for each of the seven steps. Residual plots were used to visually inspect all variables for normality. Data sphericity was assessed using Mauchly's test of Sphericity. When data violated sphericity, a Greenhouse-Geisser (<0.75) or Huynh-Feldt (>0.75) epsilon correction was used. Significant main effects were followed with post-hoc tests using a Bonferroni correction for multiple comparisons. For the computer-based perception tests, a Three Way Mixed ANOVA compared perceptual responses for within-subject effects of test stimulus, (x4: SF1, SF2, SF3 and SF12), time (x2: pre and post stair ascent), and between-subject effects of age group (x2: young and older). In the presence of non-significance between test stimuli, data were pooled across test stimuli and time within each group and a One Sample t-test was used to compare the pooled perceived riser height of the test stimuli to the veridical step height. Following ANOVA testing, Bayes Factors were computed for the perception test to determine whether non-significance in perceived riser heights between test stimuli as well as age group and time were driven by similarities. A Bayesian Three Way Repeated Measures ANOVA using JASP with default priors (JASP Team (2020). JASP (Version 0.14.1) [Windows 10]) was performed with test stimuli, age group and time as factors. Bayes Factors (expressed as BF_{01}) are reported showing the probability of the data given the null hypothesis relative to the alternative and were interpreted using the Lee and Wagenmakers classification scheme indicating levels of evidence (Quintana and Williams, 2018). Calculation of the PSE followed the same procedure outlined in chapter 2. All frequentist statistical analyses were performed in SPSS 26 (SPSS version 26.0 IBM Corp, 2019) with an alpha level of .05.

Five older adults and one young adult preferred to use the handrail during the stair ascent trials which may influence dynamic stability, therefore data from these participants were not included in statistical comparisons for MOS. In the perception tests, five older adults and four young adults showed a very high proportion of test stimulus taller responses, skewing the typical response distribution required for an accurate PSE. These data were therefore removed from all the statistical comparisons.

3.3 Results

3.3.1 Lead vertical foot clearance

Vertical foot clearances across each visual condition and each individual step are shown in Figure 3.2 for older adults and Figure 3.3 for young adults. There was a visual condition-by-age interaction effect on vertical foot clearance on step 7 ($F_{(4, 116)}=5.431$, $p<.001$, $n^2_p=.158$). Each visual condition led to an increase in vertical foot clearance for young and older adults when compared to the plain condition, but this increase was greater in older adults (1.2-2.1 cm) compared to young (0.2-0.8 cm). There was also a significant main effect of visual condition on lead vertical foot clearance on step 1 ($F_{(2.611, 75.731)}=6.36$, $p=.001$, $n^2_p=.18$). SF12 increased lead vertical foot clearance by 1.19 cm when compared to plain ($p=.017$) and increased by 1.16 cm when compared to SF1 ($p=.033$). No other differences between visual condition on step 1 were found.

3.3.2 Computer based perception tests

The Three-way mixed ANOVA did not find any interaction effects ($F_{(3, 63)}=2.396$, $p=.077$, $n^2_p=.102$), main effects between test stimuli ($F_{(3, 63)}=2.462$, $p=.071$, $n^2_p=.105$) , between groups ($F_{(1, 21)}=1.439$, $p=.244$, $n^2_p=.064$) or between time points ($F_{(1, 21)}=.002$, $p=.969$, $n^2_p=.000$). Data for each test stimulus and time were subsequently pooled for each group and compared to the veridical riser height. The test stimuli led to a significant overestimation of the riser height when compared to the veridical riser height in older adults (11% increase; *p*<.001) and young adults (13% increase; *p*<.001). Further investigation into the lack of main and interaction effects for test stimuli, age group and time using Bayesian inference showed the effect of test stimuli was 2.2 (BF_{01}= 0.453) times more likely under the alternate hypothesis than the null representing anecdotal evidence. The effect of age group and time were found to be 1.4 (BF_{01}= 1.459) and 2.3 (BF_{01}= 2.352) times more likely under the null hypothesis, each representing anecdotal evidence. The best performing interaction model of test stimuli, age group and time was found to be 3.2 (BF_{01}= 3.233) times more likely under the null hypothesis representing moderate evidence.

3.3.3 MOS, foot overhang, gaze and stair speed

Table 3.2 shows values for MOS, foot overhang and gaze duration for step 1 and step 7 across visual conditions. MOS remained unaffected by the visual conditions across all steps for both groups (*p*>.05). No differences were observed in foot overhang across visual conditions, steps or group (*p*>.05). Gaze duration on each step was not significantly different across each of the visual conditions (*p*>.05). Stair ascent speed was not significantly different between visual conditions or between groups (Older: 0.484-0.511 $m.s^{-1}$, young: 0.539-0.545 $m.s^{-1}$; *p*>.05).

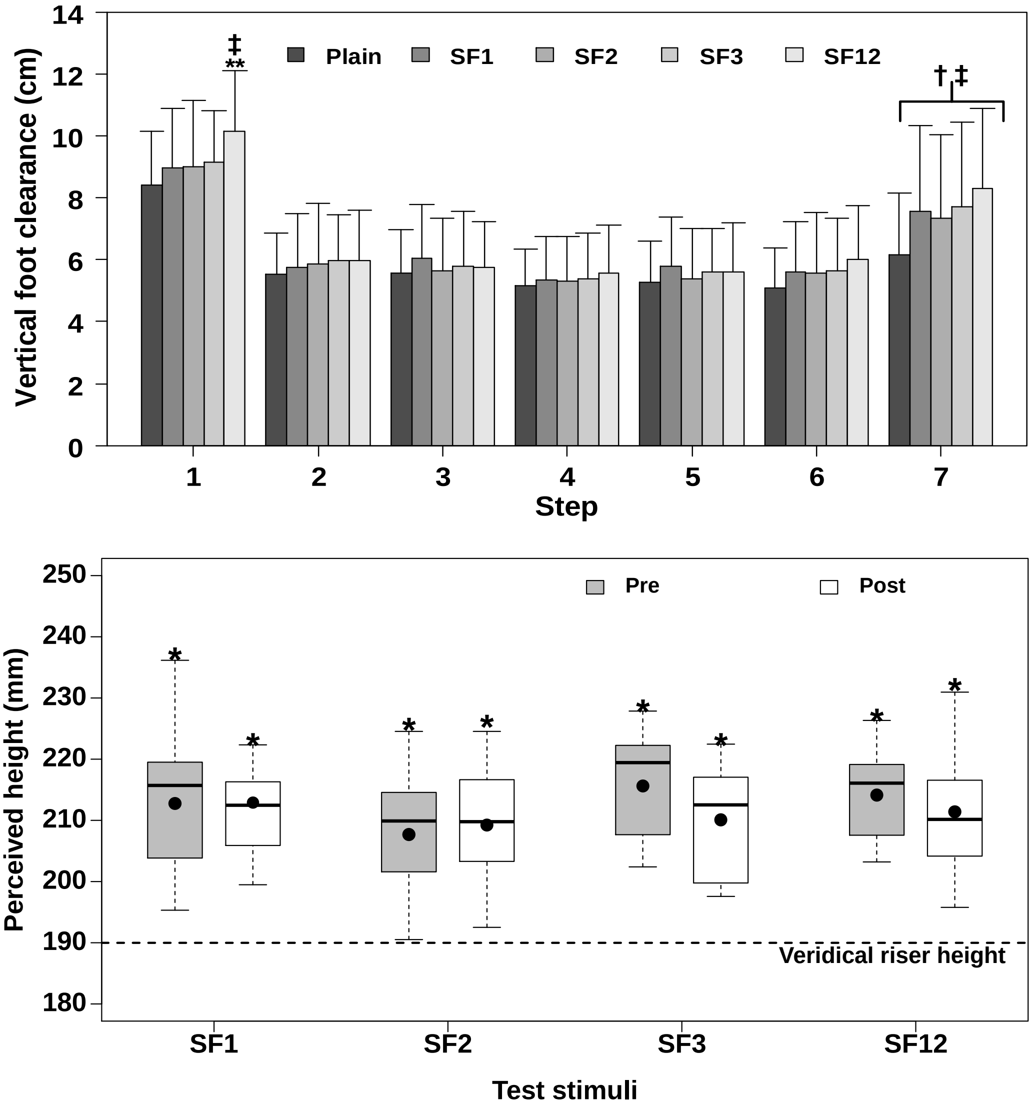


*Figure 3.2. Older adult lead vertical foot clearances over seven steps and perceived riser heights in response to each modified stair HV illusion. Box plots present the mean (●) and median (–). † Denotes an interaction effect of visual condition and age on step 7. On step 7, each modified stair HV illusion led to increased vertical foot clearances compared to plain, with greater increases in older adults when compared to young. ‡ Denotes significant increases in vertical foot clearance across all modified stair HV illusions on step 7, and SF12 for step 1 when compared to plain. ** Represents significant increases in vertical foot clearance on step 1 with SF12 compared to SF1. * Denotes significant increases in perceived riser height compared to veridical riser height across test stimuli for older adults.*

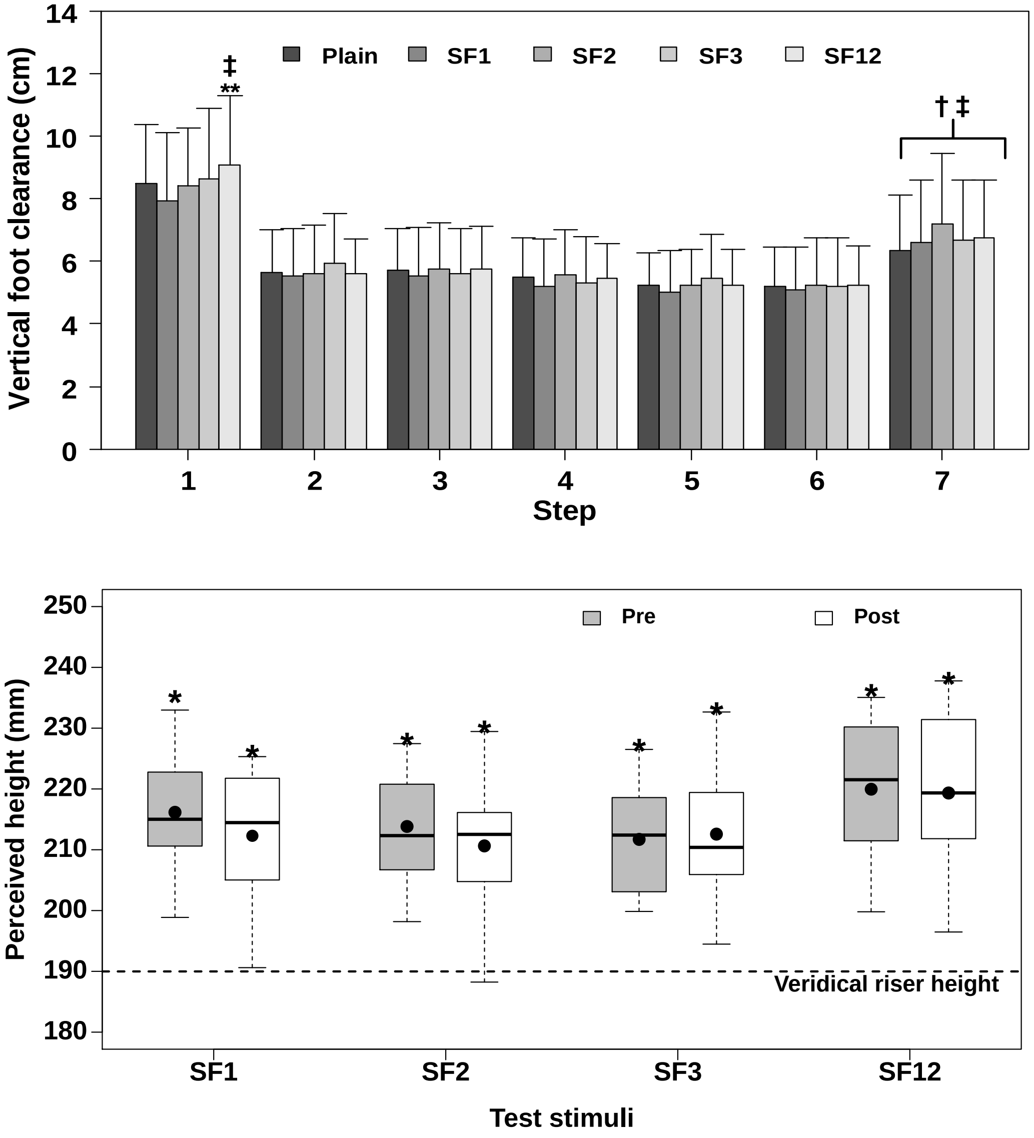


*Figure 3.3. Young adult lead vertical foot clearances over seven steps and perceived riser heights in response to each modified stair HV illusion. Box plots present the mean (●) and median (–). † Denotes an interaction effect of visual condition and age on step 7. On step 7, each modified stair HV illusion led to increased vertical foot clearances compared to plain, with greater increases in older adults compared to young. ‡ Denotes significant increases in vertical foot clearance across all modified stair HV illusions on step 7, and SF12 for step 1 when compared to plain. ** Represents significant increases in vertical foot clearance on step 1 with SF12 compared to SF1. * Denotes significant increases in perceived riser height compared to veridical riser height across test stimuli for young adults.*

Table 3.2. MOS, foot overhang and gaze durations on step 1 and step 7 across visual conditions. Negative and positive MOS values represent an extrapolated centre of mass ahead (A/P) and inside (M/L) the boundary of support, respectively. Foot overhang values represent percentages of foot length, with negative values indicating no overhang. Gaze duration values represent percentage of total fixation durations summed. Values are Mean ± 1SD.

	Step 1					**Step 7**				
	Plain	**SF1**	**SF2**	**SF3**	**SF12**	**Plain**	**SF1**	**SF2**	**SF3**	**SF12**
MOS A/P (m)										
Older	-0.13 ± 0.06	-0.14 ± 0.06	-0.15 ± 0.07	-0.14 ± 0.06	-0.12 ± 0.07	-0.11 ± 0.03	-0.13 ± 0.04	-0.13 ± 0.04	-0.13 ± 0.04	-0.12 ± 0.05
Young	-0.13 ± 0.07	-0.13 ± 0.06	-0.12 ± 0.06	-0.12 ± 0.06	-0.13 ± 0.07	-0.16 ± 0.04	-0.17 ± 0.04	-0.17 ± 0.04	-0.16 ± 0.03	-0.16 ± 0.04
MOS M/L (m)										
Older	0.11 ± 0.02	0.10 ± 0.02	0.11 ± 0.01	0.11 ± 0.02	0.10 ± 0.02	0.10 ± 0.02	0.11 ± 0.02	0.11 ± 0.02	0.10 ± 0.02	0.10 ± 0.02
Young	0.11 ± 0.01	0.11 ± 0.01	0.10 ± 0.02	0.10 ± 0.02	0.11 ± 0.02	0.11 ± 0.02	0.11 ± 0.02	0.11 ± 0.02	0.11 ± 0.01	0.11 ± 0.02
Foot overhang (%)										
Older	27.42 ± 17.91	26.46 ± 11.57	26.33 ± 13.51	26.76 ± 11.03	24.83 ± 14.75	-42.71 ± 28.88	-49.86 ± 32.47	-50.50 ± 30.62	-50.86 ± 28.68	-51.00 ± 26.52
Young	28.17 ± 7.34	28.94 ± 6.35	27.69 ± 6.56	30.17 ± 15.18	27.95 ± 8.71	-58.07 ± 33.96	-54.92 ± 33.85	-61.83 ± 36.36	-58.14 ± 37.89	-52.77 ± 34.25
Gaze duration (%)										
Older	17.72 ± 14.11	16.21 ± 12.45	18.09 ± 13.72	15.03 ± 9.54	21.18 ± 11.20	17.21 ± 8.90	21.95 ± 9.94	21.79 ± 12.02	19.64 ± 11.40	17.75 ± 11.56

3.4 Discussion

The main aim of this chapter was to assess whether a perception action link exists between perceived riser height and foot clearance in response to modified stair HV illusion designs, in older adults. We hypothesised that both young and older adults would show increases in perceived riser height and foot clearance, but to a greater extent in young adults. Findings show increases in perceived riser height with no age group differences and increases in foot clearance in both age groups, though older adults showed larger increases in foot clearance compared to young. Our hypothesis is therefore partly supported.

The findings here show indications of a perception-action link in older and young adults responding to the modified stair HV illusions. We found increases in foot clearance across all the illusions on step 7 and with SF12 on step 1 alongside increases in perceived riser heights that remained unaffected after exposure to ascending stairs with the illusion present. This perception-action link is notable for step 7, where a foot clearance increase occurred despite the increased step contacts from a longer staircase, suggesting somatosensory information here does not override the visual effects of the illusion. This may also mean that increases in foot clearance may still occur if stairs with superimposed HV illusions are encountered again by a stair user, though this requires further testing. The increases in foot clearance varied in magnitude dependent upon the modified stair HV illusion design. For step 1, SF12 resulted in a significant and larger increase in foot clearance whereas the remaining illusions resulted in foot clearances that did not increase significantly compared to plain. On step 7, SF12 resulted in the largest increase in foot clearance compared to the other designs. The foot clearance changes in response to the modified stair HV illusions here are akin to Foster et al. (2015) showing increased foot clearances with higher spatial frequency designs. We show here however significant increases in the perceived riser height with no significant differences between each visual condition from the perception test. The smaller foot clearances with SF1, SF2 and SF3 and statistical significance on step 7 only, therefore suggests the perception action link for these HV illusions is not as strong when compared to SF12. For applications on public/private stairs, this may suggest a balancing of aesthetic design and foot clearance effect should be considered, i.e. for the simplest design (SF1) an increased foot clearance is still possible, though a stronger effect (and link between perception and action) will be achieved with a slightly more featured design (SF12). This could be beneficial for choosing on stairs with extensive history of falls or where step inconsistencies mean that one step is slightly raised compared to the rest. The findings demonstrate statistically significant increases in foot clearance with the stair HV illusion, though natural variability associated with this measure might impact the overall effectiveness of the stair illusion on real world stairs. For example, the older adult participants showed within subject standard deviations of ~1cm in foot clearance, though importantly foot clearance was found to increase up to 2.1cm for this age group in response to the stair illusions. This suggests around 1cm of increase from the stair HV illusion could be within the range of natural variability leaving an effective 1.1cm foot clearance increase due to the illusion. As foot clearances of 0.5cm and below have been viewed as dangerous (Hamel et al., 2005b), a 1.1cm increase due to the illusions could still be considered substantial. The modified stair HV illusion designs may also have the added benefit of aiding safe stair descent as it incorporates an edge highlighter, positioned on the tread-edge, which helps for delineating a step edge during descent and may lead to safer foot clearances (Foster et al., 2014).

Increases in foot clearance were found to be greater in older adults (2.1cm) than in young (0.8cm) in response to the illusions. The foot clearance magnitudes we report are similar to Elliott et al. (2009), where a 0.5 cm increase in young adults was found on a single step, and Foster et al. (2015) where up to a 2 cm increase in older adults was found. These age differences in foot clearances have similarly been found by Lu, Chen and Chen (2006), who showed foot clearance over an obstacle increased with increasing height of an obstacle in older but not young adults. The visually taller steps (due to the HV illusions) in this experiment may have caused a similar effect with our older adults. These findings also corroborate the step specific effect that was found by Foster et al. (2015) on a three-step staircase whereby the increased foot clearances were pertinent to the step superimposed with the stair HV illusion. Here we show the same effect where significant increases in foot clearance were found across step 1 and 7 and no differences on steps 2-6.

The indication of a perception-action link found in this study suggests an association between the two visual streams during stair negotiation. In line with many other studies, this may be due to task specific factors and/or the type of illusion. Where perception-action disassociations are reported, online feedback of the moving limb has been found with some illusions to fine tune the motor estimation of the target illusion to the correct size (Glover, 2002; Hughes, Bates and Aimola Davies, 2008). In the absence of this feedback, the motor estimate corresponds to the illusory effect (Aglioti, DeSouza and Goodale, 1995; Gentilucci et al., 1996; Otto-de Haart, Carey and Milne, 1999). On stairs, vision is used in a feedforward manner to plan for approximately two to three steps ahead (Zietz and Hollands, 2009). Here it is likely the participants relied on visual memory of the riser heights from feedforward scanning when crossing the superimposed steps.

Older adults responded perceptually and through increased foot clearances to most of our stair/step visual treatment whereas Schofield, Curzon-Jones and Hollands (2017) did not find this. These authors did not present a stair HV-illusion stimulus but rather used subtle variations in a fine-grained texture to alter the apparent illumination of a step. Older adults are less able to see fined-grained textures and may thus not have observed the subtle changes presented. The authors reported that their participants observed no subjective differences between step conditions during the execution of the step-up task. The stair HV illusions from the current study and from Foster et al. (2015) show noticeable differences from the plain uniform condition and between stair HV illusion designs: the experimental manipulation is far more visible here than in the Schofield, Curzon-Jones and Hollands (2017) study. This suggests older adults may show more adaptive foot clearances when visual cues are noticeably different to a comparison step. This also highlights how visual information used for an action is not always guided by conscious report of visual perception (Goodale, 2014). The adaptations found here compared to Schofield and colleagues are also unlikely related to the task as Foster et al. (2015) reported a foot clearance effect in older adults with HV illusions on a single step also.

The present findings show no indication that the modified stair HV illusions lead to compromises in other measures of stair safety in young and older adults. The lack of difference in MOS suggest at the critical instance when a trip could occur, the difference in perceived and actual height do not disturb normal stair stability. A sizeable portion of participants however used handrails in this study and these participants were excluded from the margin of stability analysis. These handrail users might represent individuals with less stability, meaning it is not completely clear whether the illusion could have affected their balance if a handrail were not to be used. The presence of the modified stair HV illusions do not introduce alterations or hesitancy in stair speed or affect foot overhang. Despite the illusions also appearing visually salient to the other steps, this does not change the length of visual step inspection in older adults as supported through the lack of significant finding in gaze duration. These findings together suggest that the modified stair HV illusion designs appear not to adversely affect normal stair behaviour in older and young adults despite the benefit of increased and safer foot clearances.

3.4.1 Limitations and future considerations

The loss of gaze data resulted in a limited analysis of gaze behaviour, whereby a between age group comparison of gaze durations was not possible. Although young adults show similar conscious reports of perceived riser heights to older adults, it is not certain whether they acquire this visual information during the stepping task in the same way, especially considering the age group differences in foot clearance. An informative measurement of somatosensory adaptation here could have included superimposing the modified stair HV illusions on every step to determine whether foot clearances readjust back to the physical rather than perceived step height. However, this could result in a more exhausting stair action that compromises stair safety for an older adult. Linear increases in metabolic cost are found with increased foot lift during over ground walking (Faraji, Wu and Ijspeert, 2018). Stair walking is a more metabolically expensive form of locomotion (Bassett et al., 1997; Teh and Aziz, 2002) suggesting repeatedly increasing foot clearance could have a considerable energy expenditure consequence for older adults. Future research should also examine the effectiveness of the modified stair HV illusion on stairs with an inconsistently taller step which is a known and common hazard for stair falls (Cohen, LaRue and Cohen, 2009). Francksen et al. (2020) showed older and young adults do not adjust foot trajectories over a single mid-stair step, inconsistently taller by 1cm, suggesting slightly taller steps are not visually detected. Increasing foot clearance here with a modified stair HV illusion could help to increase foot clearance and reduce fall-risk.

3.5 Conclusion

Modified versions of the stair HV illusion were effective at increasing the perceived riser height and foot clearance on a seven-step staircase, indicating a perception-action link in older adults. This was at no apparent detriment to other stair safety measures. The modified stair HV illusion designs may be helpful in reducing older adult stair falls, but this should be evaluated next on public/private staircases, especially where there are inconsistently taller risers known to be hazardous for a fall.

Chapter 4: Using a modified stair horizontal-vertical illusion to increase foot clearance over an inconsistently taller stair-riser

The findings in this chapter were presented at The British Association of Sport and Exercise Sciences (BASES), Biomechanics Interest Group (BIG) 2021 conference and was awarded the prize for the best free communication (Appendix D, Figure D.1) (oral presentation). This study has been submitted to PLOS ONE as an original article and is currently in revision.

4.1 Introduction

The findings from the previous chapter (Skervin et al., 2021) show that modified stair HV illusions increased the perceived riser height and as a result foot clearance (up to 2.1cm) on entrance/exit stair steps where most falls are reported to occur (Startzell et al., 2000). Though a stair dimension inconsistency at the mid-stair region can still compromise stair safety (Francksen et al., 2020) and could benefit from a stair HV illusion.

The stepping action on stairs is typically an intuitive response to the step dimensions apparent to a stair user (Johnson and Pauls, 2012). This response is informed by the visually perceived step size (Elliott et al., 2009; Rhea, Rietdyk and Haddad, 2010; Foster et al., 2015) and can be fine-tuned by somatosensory feedback (i.e. when the foot lands on the stair tread) from the first few repetitions of the stepping action on a specific staircase (Heasley et al., 2004; Rhea, Rietdyk and Haddad, 2010). This somatosensory information results from foot contact on steps and the positional feedback from the movement of the lower limbs over each step. The interaction and adaptation of stair visual perception and somatosensory feedback will determine biomechanical characteristics such as foot clearance, which determine the safety of the stair negotiation. Foot clearance during a step up is a measure reflecting the distance of the foot from catching the step edge usually at the point of step edge crossing. Inadequate foot clearance can lead to a trip/fall on stairs and is characterised by foot clearances that are low and/or variable over a step edge (Hamel et al., 2005b). Foot clearance height can adapt to the visually perceived height of a step/obstacle and somatosensory feedback (Heasley et al., 2004; Rhea, Rietdyk and Haddad, 2010; Foster et al., 2015). Over a perceptually taller obstacle for example, Rhea, Rietdyk and Haddad (2010) found foot clearances initially increase in an obstacle crossing task due to the perceived obstacle size, but over repeated trials, foot clearance height reduces likely due to somatosensory feedback.

On stairs with many steps, foot clearance is reduced and more consistent over the mid-stair portion compared to stair entrance (Simoneau et al., 1991; Foster et al., 2015; Skervin et al., 2021) reflecting somatosensory learning of the step dimensions. The mid-stair action is more likely driven by this information than vision (Miyasike-daSilva and McIlroy, 2012) though this can present an issue when discrete inconsistencies in step dimensions are present mid-stair as they go visually unnoticed and lead to reduced foot clearance (Francksen et al., 2020) (Figure 4.1). Previous ergonomic reports note this as a stair safety hazard, (Johnson and Pauls, 2010; Johnson and Pauls, 2012), though only one recent study has evidenced this experimentally. Francksen et al. (2020) showed that during stair ascent, foot clearances reduced by ~0.9cm in young and older adults over a mid-stair riser that was inconsistently taller by 1cm compared to when all risers were consistent in height. Importantly, participants were unable to identify any inconsistencies in stair riser height after completing the trials. This inability to detect riser-height inconsistencies may be exacerbated on visually uniform stairs where the lack of differentiating features provide no cue for visually attending to a particular step or noticing between-step differences. Inconsistent stair dimensions are likely to go unnoticed or unreported unless a serious fall or trip event occurs, yet evidence suggests the prevalence of step inconsistencies in public are quite high. In an investigation of 80 stair fall reports, around 60% of the stairs had variance in riser height (Cohen, LaRue and Cohen, 2009). Variability in step dimensions between steps should not exceed 1% in the UK (BSI, 2010) while in the USA a variation of 4.8mm or greater between adjacent steps is prohibited and the difference between the largest and smallest step should not exceed 9.5mm (NFPA 101, 2021). However, these regulations apply to newly built stairs meaning old stairs may not conform to this or may have inconsistencies due to the stair degrading with age. Despite the safety risk, a rebuild of these stairs may be time consuming and costly.

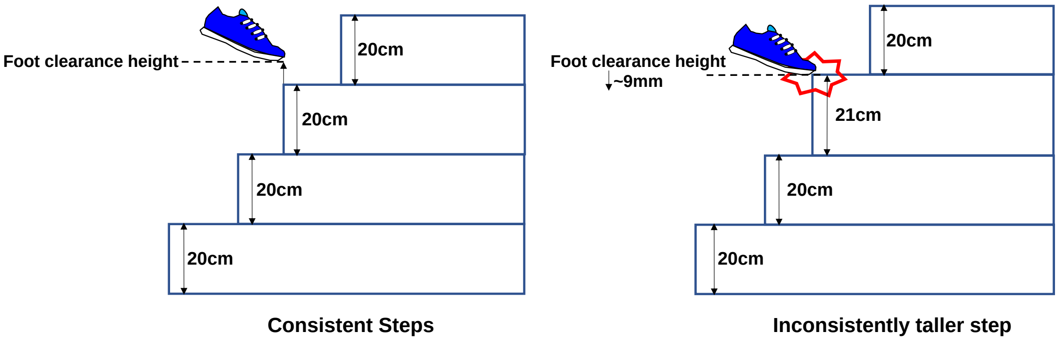


Figure 4.1 Foot clearance reduces over mid-stair steps that are inconsistently taller than the rest as the inconsistency goes perceptually unnoticed (Francksen et al., 2020).

The findings from the previous chapter (Skervin et al., 2021) show that modified stair HV illusions increased the perceived riser height and as a result foot clearance (up to 2.1cm) and raises the question as to whether the modified stair HV illusion can ameliorate the reduced foot clearances over an inconsistently taller riser. If effective, this could be a useful solution on such stair inconsistencies as there are currently no other options to circumvent this issue other than a stair rebuild. Although the previous chapter and work by Foster et al. (2015) show the illusion to have no detrimental effect on stair safety measures over consistent stair risers, visually altering the perception of a riser that is physically taller than the preceding risers may pose stability issues and requires investigating.

4.1.1 Aim

The aim of this study was to determine whether a modified stair HV illusion can ameliorate the reduced foot clearances that result over an inconsistently taller mid-stair riser and to assess whether this has unintended impact on other stair ascent safety measures. These measures included foot overhang, stair balance (margins of stability) and stair velocity which characterise other stair fall mechanisms including a stair slip or loss of balance. It was hypothesised that an inconsistently taller mid-stair riser would reduce foot clearance and that the presence of a modified stair HV illusion superimposed onto the inconsistently taller riser would increase foot clearance.

4.2 Method

4.2.1 Participants

Twelve young adults (Mean (1SD), age: 22 (3) years, height: 1.8 (0.1) m, mass: 81.2 (19.3) kg, visual acuity: -0.16 (0.08) LogMAR, contrast sensitivity: 2.18 (0.32) LogCS; 9 males) were recruited from the University and local community and provided written informed consent to participate. All participants were free from visual and physical/neurological impairment that would prevent them from climbing stairs. Vision was assessed using The Freiburg Visual Acuity Test (Bach, 1996). All participants were naïve to the illusion and its effect from previous studies. This study received institutional ethical approval (17/SPS/002) and conformed to the declaration of Helsinki.

4.2.2 Protocol

Participants ascended a seven-step custom-built instrumented staircase at a self-selected speed under three different stair riser conditions: i) all seven steps consistent in riser height (consistent), ii) a 1cm increase in step 5 riser height only (inconsistent), and iii) a 1cm increase in step 5 riser height only, superimposed with a stair horizontal-vertical illusion (illusion) (Figure 4.2). For the consistent stair condition, each step had a riser height of 20cm. For the inconsistent and illusion stair conditions, step 5 had a rise height of 21cm whilst the remaining steps had rise heights of 20cm. All steps had a going length of 25cm irrespective of stair condition. These dimensions fall within UK building regulations (Gov, 2010). Each stair condition was performed as a block of five successful trials. Participants began by completing the consistent stair condition first, but the order of inconsistent and illusion stair conditions were counterbalanced between participants. Following the stair trials, participants completed a computer-based perception test to determine the presence of a perceptual effect in response to the illusion.

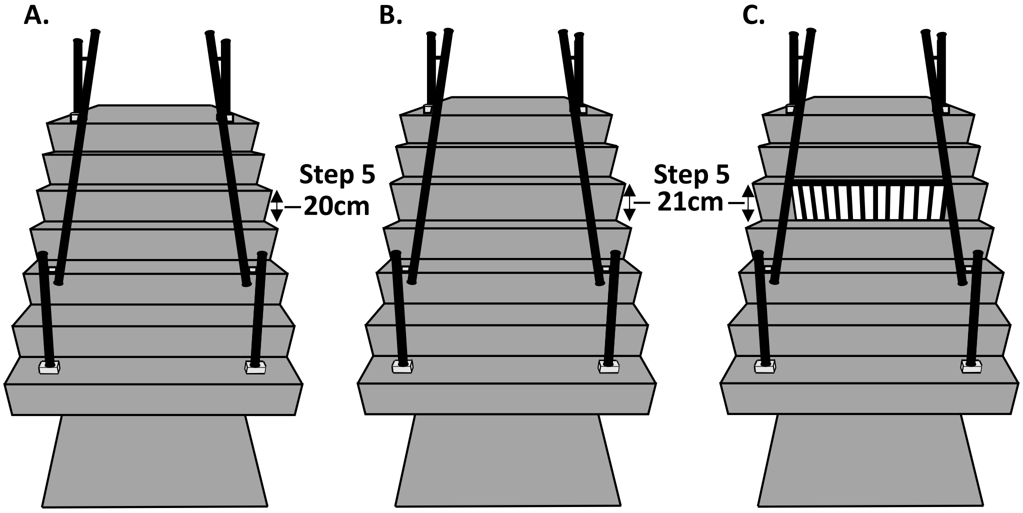


Figure 4.2 Stair conditions. A= consistent, B= inconsistent and C= illusion. Step 5 riser height for stair conditions B and C was increased by 1cm. The stair HV illusion design on stair C was characterised by a 70-30% mark space ratio between the white and black stripes on the riser aspect respectively with an abutting edge highlighter on the step going. This design was used as it showed the strongest perception-action link from the previous study (Skervin et al., 2021) .

Trials began approximately two/three steps away from the staircase. Participants were instructed to cross the first step with the same self-selected foot for each trial, ascend the stairs in a step-over-step manner and continue walking to the end of the top landing after crossing the last step. Upon return to the start position, participants were asked to step over two low height obstacles to disrupt any potential somatosensory interference from descending the stairs. When changing between stair conditions, participants were asked to leave the room and were instructed that something may or may not change on the stairs. Participants were not informed of the 1cm increase in riser height change or the purpose of the superimposed illusion. All participants completed the trials without handrail use. Participants wore tight clothing, flat shoes and were familiarised with the protocol. Commercially available grey floor coverings were used on the laboratory staircase to create a visually uniform stair appearance. The stair HV illusion riser design (Figure 4.2) was printed in a matte finish, cut to size, and reinforced with card. A 5.5cm edge highlighter was used on the going of step 5 to complete the illusion (Foster et al., 2015).

A 26-camera motion capture system (Vicon MX, Oxford Metrics, UK) captured whole body kinematics at 120 Hz. The Plug-in Gait marker set (without arms) was used to model head, trunk, pelvis and lower body kinematics with additional tracking markers and clusters placed on the head and lower limbs. A static calibration was captured to acquire the modelled body segments’ marker coordinates. A digitising wand (C-Motion, Germantown, MD, USA) was used to create virtual landmarks on the toe and heel-tips of participants’ shoes. Toe-tip landmarks were created on the most anterior-inferior aspect of the shoe, heel-tip landmarks were created at the most posterior-inferior aspect of the shoe. Step edge locations were defined with virtual landmarks using the digitising wand, and these were referenced to a marker cluster affixed to the stairs.

Marker data were labelled, and gap filled (spline method with maximum gap of 12 frames) in Vicon (Vicon Nexus 2.6, Oxford Metrics), and exported as c3d files for analysis using Visual 3D (C-Motion, Germantown, MD, USA). Marker data were filtered using a fourth order Butterworth bidirectional filter (cut-off frequency 6Hz). Outcome measures included lead vertical foot clearance, foot overhang, margins of stability (MoS) in the anteroposterior and mediolateral directions, and stair-climbing velocity.

Lead vertical foot clearance, defined as the vertical distance of the virtual toe tip landmark to the step edge was extracted at the point where the difference in anteroposterior position between the step edge and virtual toe tip landmark was zero. Foot overhang was defined as the distance between the virtual heel tip landmark and the virtual step edge location(s) and was extracted at the point the trail limb crossed the step edge. Foot overhang was calculated as a percentage of foot length.

Centre of mass (CoM) was generated as a link model-based item in Visual 3D based on Dempster’s regression equations (Dempster, 1955). Stair-climbing velocity was calculated as the first derivative of the CoM anteroposterior trajectory from the start of the trial to initial contact on the top landing of the trailing foot. Margins of stability were calculated and defined in the anteroposterior direction as the distance between the extrapolated CoM (xCoM) and the virtual toe tip landmark and in the mediolateral direction as the distance between the xCoM and 5th Metatarsal head (Hof, Gazendam and Sinke, 2005; Bosse et al., 2012; Novak et al., 2016). In the anteroposterior direction a negative margin of stability value represents an xCoM anterior to the boundary of support indicating instability. In the mediolateral direction a negative value represents an xCoM that is lateral to the boundary of support indicating instability.

xCoM was defined as:

$$xCoM = pCoM + vCoM/\sqrt{(gl^{-1})}$$

where pCoM is the anteroposterior/mediolateral position of the CoM, vCoM is the instantaneous anteroposterior/mediolateral velocity of the CoM, g is acceleration due to gravity, and l is the absolute distance between the CoM and the ankle joint centre. The anteroposterior and mediolateral margin of stability were calculated at the point of lead vertical foot clearance over each step as this represents the most dangerous point for a trip.

Aside from stair-climbing velocity, all outcome measures were calculated for each stair condition on step 4, 5 and 6 to determine whether each condition influenced behaviour before, on and after step 5.

4.2.3 Visual perception test

The computer-based perception test using a forced choice psychophysical procedure programmed in PsychoPy (Psychophysics software in Python) from Chapter 2 assessed the perceived height of step risers when superimposed with the modified stair HV illusion. This test involved the comparison of an outlined stair image superimposed with versions of modified stair HV illusions (Foster et al., 2015) on the bottom riser (fixed riser height) to plain outlined stair images with varying bottom riser heights. Participants then selected the stair that appeared to have the tallest bottom riser height over repeated trials. Perceived riser height was estimated by fitting a psychometric function to the relative step height judgments and finding the point of subjective equality between the patterned and plain steps. This test included the modified stair HV illusion that was present in the stair ascent trials (70-30% mark space ratio design; Figure 4.2), allowing us to understand how participants may have visually perceived the step riser height during the stair ascent trials in the illusion condition. The programming setup of the perception test included three other previously developed modified stair HV illusion designs. These designs were not included in the stair ascent assessment since no differences in perceived riser height were found between all versions (One-Way Repeated Measures ANOVA; $p>.05$). Readers are referred to chapter 2 (Skervin et al., 2021) for our investigation of differences between illusion designs and for further details about this perception test.

4.2.4 Statistical analysis

For each participant, the average of 5 trials for each condition were used for statistical analysis. Residual plots were used to visually inspect all variables for normality. A One-Way Repeated Measures ANOVA compared kinematic variables for within-subject effects of stair condition (x3: consistent, inconsistent, illusion). Separate ANOVAs were performed for each step. Data sphericity was assessed using Mauchly's test of Sphericity. When data violated sphericity, a Greenhouse-Geisser (<0.75) or Huynh-Feldt (>0.75) epsilon correction was used. ANOVA effect sizes are reported as partial eta squared (n^2_p), for which the thresholds are small (0.01), medium (0.06) and large (0.14). Significant main effects were followed with post-hoc tests using a Bonferroni correction for multiple comparisons. Effect sizes for post hoc comparisons are represented as Hedges *g* for which the thresholds are small (0.2), medium (0.5) and large

(0.8) (Lakens, 2013). A One Sample t-test was used to compare the perceived riser height of the stair HV illusion to the true step height. Statistical analyses were performed in SPSS 26 (SPSS version 26.0 IBM Corp, 2019) with an alpha level of .05. Centre of mass data were incomplete for one participant meaning margin of stability and stair velocity comparisons were performed with eleven participants. All results are reported as mean (1SD).

4.3 Results

4.3.1 Lead vertical foot clearance

A significant main effect of stair condition was found over step 5 ($F_{(2, 22)}$=12.413, *p*<.001, n^2_p=.530). The inconsistent condition reduced foot clearance by 0.8cm when compared to the consistent (*p*=.007, *g=.689*), and the illusion condition increased foot clearance by 1.1cm when compared to the inconsistent condition (*p*=.002, *g=1.043*) (Figure 4.3). No significant differences were found between the consistent and illusion condition (*p*=.615). No significant differences were found between conditions on step 4 and step 6 (Table 4.1; *p*≥.218).

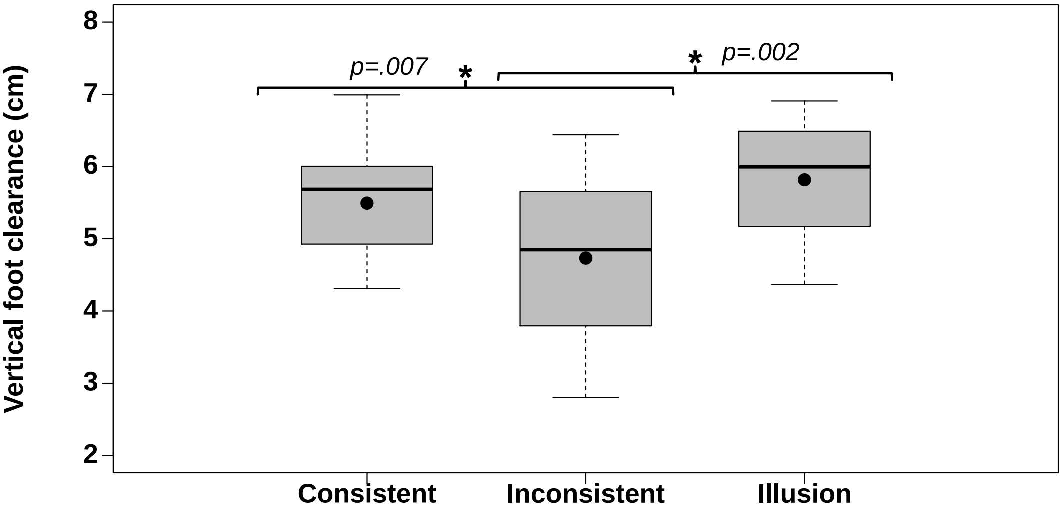


*Figure 4.3 Vertical foot clearance on step 5. Box plots present the mean (●) and median (–). * = significant difference between conditions inside brackets.*

4.3.2 Foot overhang

A significant main effect of stair condition was found on step 5 ($F_{(2, 22)}$=4.612, *p*=.021, n^2_p=.295). The illusion condition reduced foot overhang by 4% compared to the inconsistent condition (*p*=.029, *g=.327*) but was not significantly different to the consistent condition (*p=.541*) (Figure 4.4). No differences were found on step 5 when the consistent condition was compared to the inconsistent condition (p=.387). No significant differences were found between conditions on step 4 and step 6 (p≥*.165*).

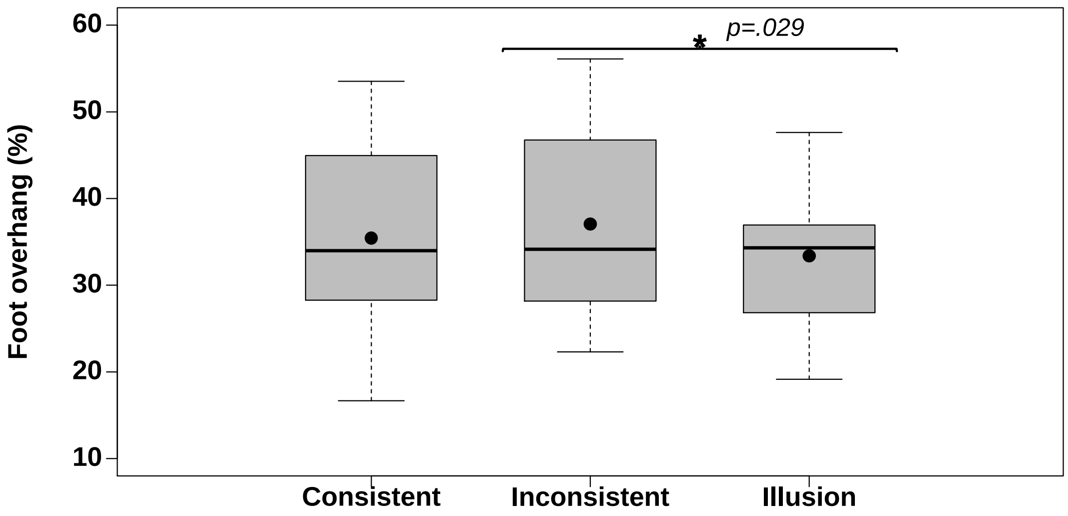


*Figure 4.4 Foot overhang on step 5. Box plots present the mean (●) and median (–). * = significant difference between conditions inside brackets. Plots represent percentages of foot length.*

4.3.3 Anteroposterior margins of stability

For all conditions, the anteroposterior margin of stability was negative at the point of lead vertical foot clearance (Figure 4.5). No significant main effect of stair condition was found on step 5 ($F_{(2, 20)}$=2.391, p=.117, n^2_p=.193). A significant main effect of stair condition was found on step 4 ($F_{(1.294, 12.941)}$=6.288, p=.020, n^2_p=.386). The illusion condition led to a more negative margin of stability when compared to the inconsistent condition by 0.9cm (p=.031, g=*.216*) but illusion was not significantly different to the consistent condition (p=.055). No differences were found on step 4 when comparing consistent to the inconsistent condition (p=*.366*; Table 4.1). A significant main effect of condition was found on step 6 ($F_{(2, 20)}$=3.777, p=.041, n^2_p=.274), but post hoc comparisons revealed no differences between stair conditions (p≥.111; see Appendix E, Table E.1 for unadjusted post hoc tests).

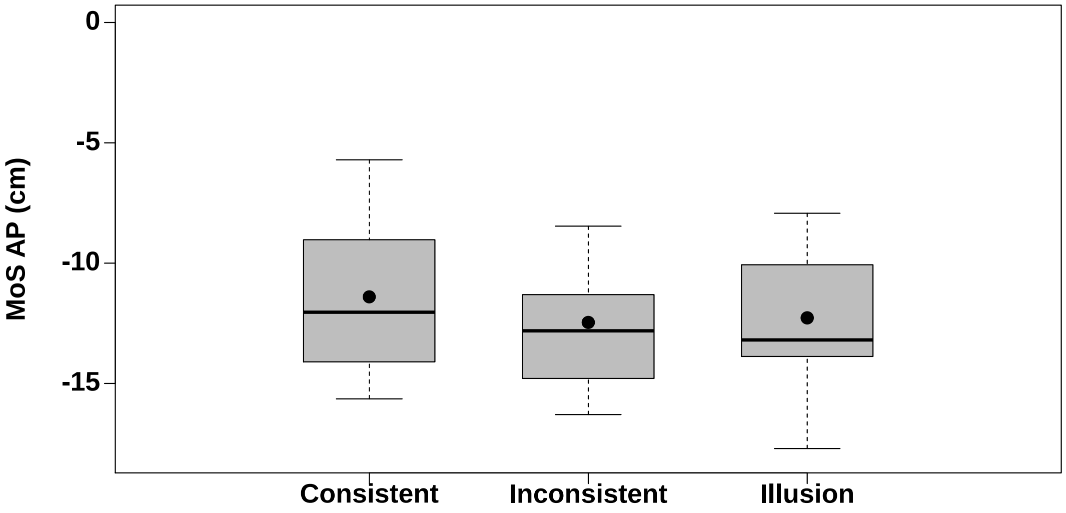


Figure 4.5 Anteroposterior MoS on step 5. Box plots present the mean (●) and median (–). Negative anteroposterior MoS values represent an xCoM ahead (anterior) of the boundary of support.

4.3.4 Mediolateral margins of stability

For all conditions, the mediolateral margin of stability was positive, indicating stability at the point of lead vertical foot clearance (Figure 4.6). No significant main effect of condition was found on step 5 ($F_{(1.320,\ 13.203)}$=1.231, *p*=.303, n^2_p=.110). A significant main effect of condition was found on step 4 ($F_{(2,\ 20)}$=7.004, *p*=.005, n^2_p=.412). The illusion (15.2 (2.2) cm, *p*=.009) and inconsistent (15.1 (2.1) cm, *p*=.015) condition led to greater stability compared to the consistent condition (14.2 (1.8) cm; Table 4.1). No significant differences were found between the illusion and inconsistent condition (*p=1*.0). A significant main effect of condition was found on step 6 ($F_{(2,\ 20)}$=3.684, *p*=.043, n^2_p=.269), but post hoc comparisons revealed no differences between stair conditions (*p*≥.054; see Appendix E, Table E.1 for unadjusted post hoc tests).

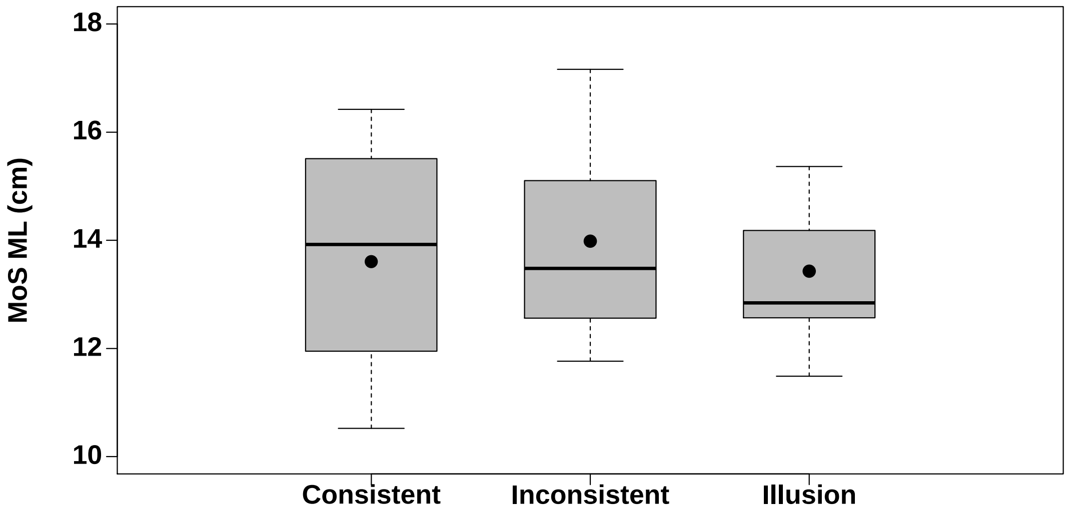


Figure 4.6 Mediolateral MoS on step 5. Box plots present the mean (●) and median (–). Positive mediolateral values represent an xCoM that is inside (medial) the boundary of support.

4.3.5 Stair-climbing velocity and perceived riser heights

Stair-climbing velocity did not significantly differ between stair conditions (consistent = 0.5 (0.1) $m.s^{-1}$, inconsistent = 0.5 (0.1) $m.s^{-1}$, illusion = 0.5 (0.04) $m.s^{-1}$) ($F_{(3, 33)}$=.788, *p*=.509, $n^2{}_p$=.067). In the computer-based perception test, the step superimposed with the HV illusion was perceived to be significantly taller than the true height by 12% (*p*<.001, *g=2.216*).

Table 4.1. Values for vertical foot clearance, foot overhang, anteroposterior MoS and mediolateral MoS on steps 4, 5 and 6 across conditions.

	Step 4			**Step 5**			**Step 6**		
	Consistent	**Inconsistent**	**Illusion**	**Consistent**	**Inconsistent**	**Illusion**	**Consistent**	**Inconsistent**	**Illusion**
Vertical foot clearance (cm)	5.0 (1.2)	4.7 (0.8)	4.9 (1.0)	5.5* (1.0)	4.7 (1.1)	5.8* (1.0)	4.9 (1.0)	4.7 (0.9)	5.1 (0.8)
Foot overhang (%)	39.2 (11.1)	41.4 (10.7)	40.5 (9.6)	35.4 (11.5)	37.1 (11.6)	33.4* (10.0)	32.0 (11.8)	34.0 (11.4)	33.9 (11.1)
Anteroposterior MoS (cm)	-10.0 (3.9)	-10.9 (4.2)	-11.8* (3.7)	-11.4 (3.3)	-12.5 (3.1)	-12.2 (2.9)	-11.7 (3.3)	-12.9 (3.7)	-12.3 (3.3)
Mediolateral MoS (cm)	14.2 (1.8)	15.1† (2.1)	15.2† (2.2)	13.6 (2.1)	14.0 (1.8)	13.4 (1.6)	14.3 (0.9)	15.3 (1.5)	14.5 (1.7)

Negative and positive MoS values represent an xCoM ahead (anteroposterior) and inside (mediolateral) the boundary of support, respectively.

Foot overhang values represent percentages of foot length.

*****Denotes significant difference compared to inconsistent condition.

†Denotes significant difference compared to consistent condition.

4.4 Discussion

This study is the first to provide evidence that the presence of a modified stair HV illusion can ameliorate the effects of previously reported reduced foot clearance over an inconsistently taller mid-stair riser.

The reduced foot clearance observed for the inconsistent stair condition (0.8cm) corroborates the previously identified stair safety issue that individuals do not adapt to such riser height increases (Francksen et al., 2020), likely due to the stair riser increase going unnoticed. Here we show a reduction in foot clearance that is comparable in magnitude to the inconsistency of the step and similar to the reduction (0.9cm) reported by Francksen et al. (2020). Whilst Francksen et al. (2020) created an inconsistency on the third step, our inconsistency occurred on the fifth step, suggesting the lack of foot clearance adaptation we found could have been driven by somatosensory learning from as early as two complete steps up.

Foot clearance for the illusion compared to inconsistent stair condition increased, suggesting the modified stair HV illusion is an effective visual cue that can offset the foot clearance reductions to a safer distance. No changes to foot clearance on step 4 or step 6 across stair conditions also indicate that the foot clearance increase is pertinent to the step the illusion is placed upon, supporting previous findings (Foster et al., 2015; Skervin et al., 2021). Our computer-based perception test also showed increases in perceived riser height in response to the same modified stair HV illusion we used during the stair ascent trials. This, alongside accompanying increases in foot clearance, represents a perception-action link. This is important as studies involving motor control in response to illusions sometimes show dissociations between the perceptual response and motor action (Aglioti, DeSouza and Goodale, 1995), though this may also be linked to methodological factors (Kopiske et al., 2016).

On Step 5, the modified stair HV illusion resulted in reduced foot overhang compared to the inconsistent condition, meaning a greater portion (4%) of the foot was in contact with the step. Our effect sizes however indicate that this was a small effect. Greater foot contact length on a step reduces the likelihood of a slip occurring and may be related to the presence of the edge highlighter on the going of the step. Previous findings indicate that the presence and positioning of an edge highlighter provides a visual cue that affects where the foot is placed when descending stairs (Foster et al., 2014) and may have a similar effect for stair ascent. This greater foot contact length may also be a result from the increased foot clearance height, as the foot would likely have longer time to travel forwards and downwards onto the step.

On step 4, there was a more negative anterior margin of stability for the illusion condition compared to the inconsistent stair condition, though a negative anterior margin of stability is expected between steps as part of the natural forward movement (Kuo, Donelan and Ruina, 2005) on stairs. Minimal difference in foot overhang on step 4 between conditions indicates that this change was not a result of changes to the base of support positioning (i.e., anterior foot placement) on the step and more likely a change in the CoM control. This might reflect a more forward leaning upper body posture and head flexion to visually focus on the step with the modified stair HV illusion, particularly as this step would appear noticeably different to the other steps. During stair descent Bosse et al. (2012) showed more negative anterior margin of stability at touch down and an associated increased trunk flexion angle trend which could be the case here. On step 4 a significant increase in mediolateral stability was observed in the inconsistent and illusion condition when compared to the consistent condition. Importantly, the mediolateral margin of stability was positive across all conditions indicating stability and this direction of change for the inconsistent and illusion condition was towards a safer margin of stability. The reason for this change is not clear but may be related to the step height change rather than the step appearance given the null difference between the illusion and inconsistent. Over the entire stair ascent period, no significant differences between conditions were observed for stair velocity. This suggests that the step manipulations do not significantly introduce overall stair hesitation.

For an inconsistent riser, the modified stair HV illusion may have advantages over the use of an edge highlighter alone. On a single step, edge highlighters appear not to increase foot clearance during the step up (despite the added saliency), whereas a modified stair HV illusion does (Foster et al., 2015). This means on an inconsistent riser a stair HV illusion would more likely increase foot clearance compared to an edge highlighter. The stair HV illusion incorporates an edge highlighter in its design which can aid stair descent safety (Foster et al., 2014) and could be a possible solution for inconsistent goings, though future work should address this. The riser stripes alongside the top edge highlighter provides greater saliency to the step and may encourage visual attention, particularly for an inconsistent riser which goes unnoticed. The modified stair HV illusion could therefore be a practical solution for inconsistently taller steps on public stairs, where a rebuild is usually the only option.

4.4.1 Limitations and future considerations

Here a stair safety benefit has been demonstrated (i.e., increased foot clearance) through superimposing a modified stair HV illusion on an inconsistently taller riser, in young adults. Future research should determine whether older adults, who fall with more serious consequences than young adults, respond in a similar way. Francksen et al. (2020) showed no differences in reduced foot clearances between young and older adults over an inconsistently taller stair riser, suggesting findings from the current study may translate to older adults. Our previous work indicates a perception-action link in older adults in response to the modified stair HV illusion superimposed on stairs (Skervin et al., 2021) (chapter 3), so it is plausible that older adults could exhibit increases in foot clearance in response to a stair HV illusion placed onto an inconsistently taller riser in the same way as young adults in the current study. For our consistent condition we chose a plain/uniform stair surface without edge highlighters as these are not always present on stairs. Foster et al. (2015) showed foot clearance does not increase significantly with the presence of an edge highlighter alone but does when a stair HV illusion is used. Here it is likely an increase in foot clearance would still occur with a stair HV illusion if all steps had edge highlighters present, though this should be tested explicitly in future. This study tested more males than females, therefore care should be taken when generalising the current findings to females since sex based differences were previously reported to affect centre of mass control (Hsue and Su, 2014). Future investigations should also assess the efficacy of using the modified stair HV illusion on stairs in public where cases of inconsistently taller risers are reported. To do this, a method of detecting its effectiveness in the public without the need for complex motion capture systems typically used in laboratory environments is needed.

4.5 Conclusion

Here evidence is shown that the presence of a modified stair HV illusion can offset the effects of reduced foot clearance over an inconsistently taller mid-stair riser. Importantly, there were no detrimental effects on other measures of stair safety over the inconsistently taller step. The modified stair HV illusion could be a beneficial solution on stairs that have an inconsistent riser and future research should determine its efficacy in real-world environments with younger and older adult stair users.

Chapter 5: Accuracy and precision of a custom photogate setup to measure foot clearance on stairs

5.1 Introduction

Insufficient foot clearance is one of the primary mechanisms for a fall over trip-hazards during activities of daily living. In particular on stairs, a fall can lead to severe injuries and serious consequences for older adults (Jacobs, 2016). The risk of tripping or falling on stairs is typically assessed in a laboratory environment by measuring the distance from the foot to the step/stair edge when crossing a step edge (Hamel et al., 2005; Foster et al., 2015; Kesler et al., 2016). A laboratory environment allows for a detailed and controlled assessment of foot clearance though sometimes at the consequence of natural stair walking behaviour, usually due to the requirement of wearing obtrusive retroreflective markers in an unnatural environment.

Optoelectronic systems are typically used in laboratories and are considered the gold standard for measuring stair behaviour. These comprise multicamera systems that project and track infrared light reflected from retroreflective markers placed onto an individual to model body segments of interest and are accurate within millimetres (Topley and Richards, 2020). To capture foot clearance, retroreflective markers are routinely placed on the shoe to define a foot segment, and the shoe tips (Foster et al., 2015) and/or plantar surfaces (Telonio et al., 2013) of the shoe are then derived using virtual landmarks tracked by rigid marker clusters. The position of these virtual landmarks can be identified through digitising tools (such as marker probes/digitising wands (Telonio et al., 2013; Foster et al., 2015), a microscribe (Hamel et al., 2005b) or by tracing the border of the shoe (Ackermans et al., 2019; Francksen et al., 2020). For optoelectronic systems, multiple cameras are required for accurate measurement and specialist software is needed meaning these systems are not easily portable, require significant setup procedures (including placing markers on participants) and are expensive to purchase.

More portable alternatives measuring foot clearance include inertial measurement units (Benoussaad et al., 2016), 2D video capture (Zult et al., 2019) and distance sensors placed on the soles of shoes (Selvaraj et al., 2018). In comparison to an optoelectronic system, inertial measurement units have shown a low average error of 0.74cm in foot clearance measurement (Benoussaad et al., 2016) whilst 2D cameras have shown a large error of 4.5cm (Zult et al., 2019). However, these methods are limited by several factors, such as the requirement of securing instrumentation to the participant, applying corrections to the signal output, or needing a camera with high capture rate and resolution.

5.1.1 Aim

Here a prototype custom-built photogate setup has been developed that is portable, inexpensive, requires no signal corrections and can be placed onto stairs instead of directly on the participant to measure foot clearance over a single step on stairs. Developing such a system may help towards making real world stair assessments a more feasible option for investigators.

The aim of this study was to determine the precision and accuracy of a photogate setup against an optoelectronic system.

5.2 Method

5.2.1 Participants

Twelve young adults (age 22 ± 3 years (range: 18-27), height 1.8 ± 0.1 m, mass 81.2 ± 19.3 kg) with no physical or neurological impairment were recruited from the University and local community and provided written informed consent to participate. This study received institutional ethical approval (17/SPS/002) and conformed to the declaration of Helsinki.

5.2.2 Experimental design

The photogate setup was first validated by comparing the Vicon measured height of a marker (attached to a rigid object) passed over a step edge, to the marker height measured by photogates over 150 trials. Photogates were abutted to a step edge to capture the measurement at step edge crossing. The marker was affixed to the bottom of a rigid object such that the marker would break the photogates first as opposed to the body of the rigid object. The marker was passed linearly over the step edge in an anterior direction.

Participant measurements involved completing 25 trials ascending a seven-step custom-built staircase at a self-selected speed. Trials began approximately two/three steps away from the staircase from the same starting position. Participants ascended the stairs in a step-over-step manner, crossing the first step with the same self-selected foot for each trial. Vertical foot clearance over a single step edge (step 5) was captured using a 26-camera motion capture system at 120Hz (Vicon MX, Oxford Metrics, UK) and through the photogate setup. Each step had a rise height of 20cm and a going length of 25cm. The Vicon and photogate measurements were performed concurrently within each trial.

5.2.3 Using Vicon to measure marker height and foot clearance

Retroreflective markers were placed on the 1st metatarsal head, 5th metatarsal head and the hallux with an additional three-marker cluster on the dorsal surface of the mid-forefoot. A digitising wand (C-Motion, Germantown, MD, USA) was used to create virtual landmarks on the toe tip of participants’ shoes. A single toe-tip landmark was created on the most anterior, inferior aspect of the shoe. Location of step edge 5 was also defined using virtual landmarks. Vertical foot clearance, defined as the vertical distance of the virtual toe tip landmark to the step edge was extracted at the point where the difference in anterior/posterior position between the step edge and virtual toe tip landmark was zero. Single marker height was also extracted at the point where the difference in anterior/posterior position between the step edge and marker was zero. Marker data were labelled, and gap filled in Vicon (Vicon Nexus 2.6, Oxford Metrics, UK), and analysed using Visual 3D (C-Motion, Germantown, MD, USA). Marker data were filtered using a fourth order Butterworth bidirectional filter (cut-off frequency 6Hz).

5.2.4 Using photogates to measure marker height and foot clearance

Commercially available laser diodes (WayinTop, 5539) and phototransistors (Vishay TEPT4400) were used to create 22 vertically arranged photogates that abutted the step edge. Each photogate was arranged one above the other on wooden blocks positioned on the tread (going) of step 5 to capture the height of the single marker for the validation trials and foot clearance for the participant trials (Figure 5.1A). Each photogate was created by manually aligning the light projected by the laser diode to its height respective phototransistor, spaced approximately 1 m apart across the width of the step tread. Each photogate was vertically separated by approximately 0.6cm and the first and last photogate were positioned 2cm and 14.9cm above the step surface, respectively (Figure 5.1B). Laser diodes were powered by a 5 volts DC, mains connected power supply and were connected in parallel. Phototransistors were connected to General Purpose Input Output (GPIO) connections on a Raspberry Pi (Model 4, Raspberry Pi Foundation, UK) using pull-down resistors (10kΩ). The 3.3 volts power supply on the Raspberry Pi was used to power the phototransistors in a parallel circuit. The height of the lowest photogate broken at step edge crossing was used for the single marker and foot clearance heights. Single marker height was extracted as the lowest photogate broken. The foot clearance height was taken as the lowest photogate broken within a time window of 0.0083s from the first photogate breaking to extract measurements during the period of foot to step edge clearance only. The GPIO connections were programmed using Python (Python Software Foundation) to continually listen for the falling edge (high to low digital state change) that occurred when a photogate was broken and to log the photogate height and epoch time at which this occurred to a text file (Appendix F, Figure F.1).

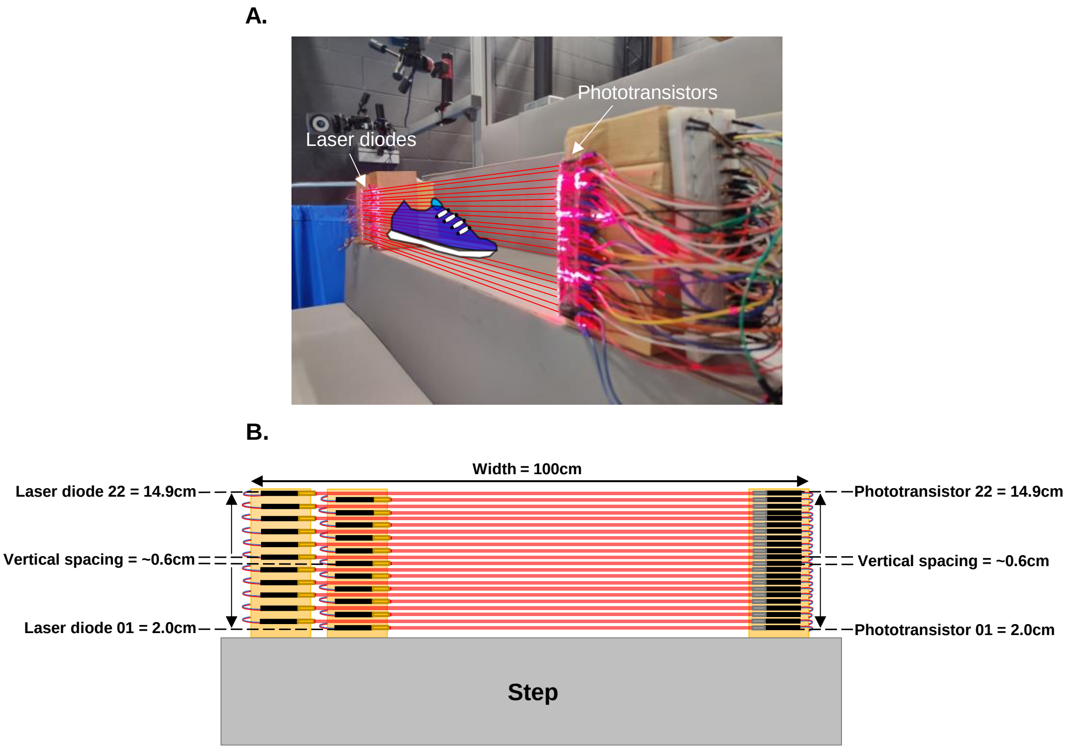


Figure 5.1 A. Photogates abutted to a single step edge of a seven-step staircase. Lasers were positioned on the left and the receivers were positioned on the right. Two blocks were used for laser diode affixation to allow space above and below the laser diodes for fine adjustments when aligning the photogates. Annotations illustrate the photogate beams and the measurement of foot clearance. The foot clearance height equals the lowest photogate broken by the shoe (seventh photogate in the annotation, which had a measured height of 5.94cm). B. Illustrated frontal plane view of the photogate dimensions and setup.

5.2.5 Statistical analysis

Residual plots were used to visually inspect the foot clearances for normality. A limits of agreement analysis (Bland and Altman, 1986) was performed and Bland-Altman plots were created to assess how close the photogate measurements agreed with the Vicon measurements for the single marker and foot clearance trials. Such analysis determines the mean difference between the two measurement methods (bias/accuracy), along with 95% agreement limits which determine the precision (range of agreement). Pearson’s Correlation was used to assess the relationship between the photogates and Vicon for the single marker and foot clearance trials. Statistical analyses were conducted using R (R Core Team, 2020) and the BlandAltmanLeh software package (Bernhard Lehnert, 2015).

5.3 Results

For the single marker height measurements (150 trials), the limits of agreement analysis revealed a mean difference of -0.14 cm (photogates overestimated foot clearance) between the two measurement systems, with an upper and lower limit (precision) of 0.35cm and -0.64 cm respectively (Figure 5.2). The mean and standard deviation for the photogate and Vicon measurements were 7.27 ± 3.38 cm and 7.13 ± 3.42 cm, respectively. A very strong positive correlation was found for the marker height measurements between the photogates and Vicon ($r = .99$, $n = 150$, $p<.0001$).

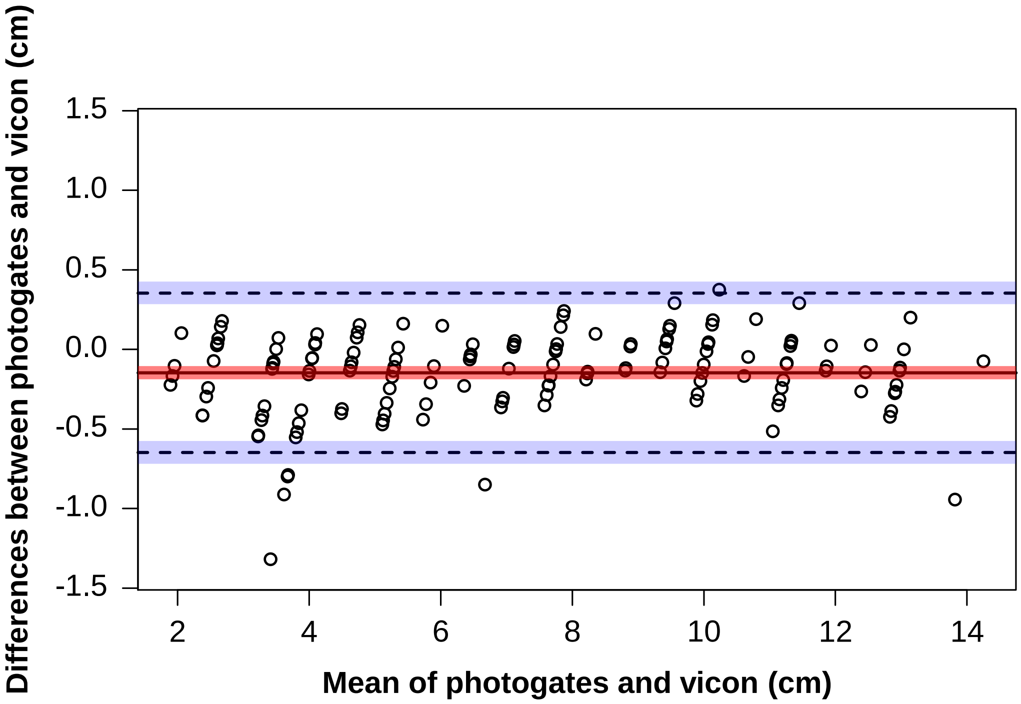


Figure 5.2 Bland-Altman plot representing the mean (x axis) and differences (y axis) of a marker height measured by Vicon and the photogates. Limits of agreement are indicated as dotted lines with 95% confidence intervals (blue shading). The bias is represented as a solid line with 95% confidence intervals (red shading).

A total of 296 trials were used for the foot clearance measurement comparison (data were missing from four trials due to incomplete recordings). For foot clearance, the limits of agreement analysis revealed a mean difference of -0.15 cm (photogates overestimated foot clearance) between the two measurement systems, with an upper and lower limit of 1.27cm and -1.58 cm respectively (Figure 5.3). The mean and standard deviation for the photogate and Vicon measurements were 5.26 ± 1.22 cm and 5.11 ± 1.27 cm, respectively. A very strong positive correlation was found between the photogates and Vicon foot clearances ($r = .83$, $n = 294$, $p<.0001$).

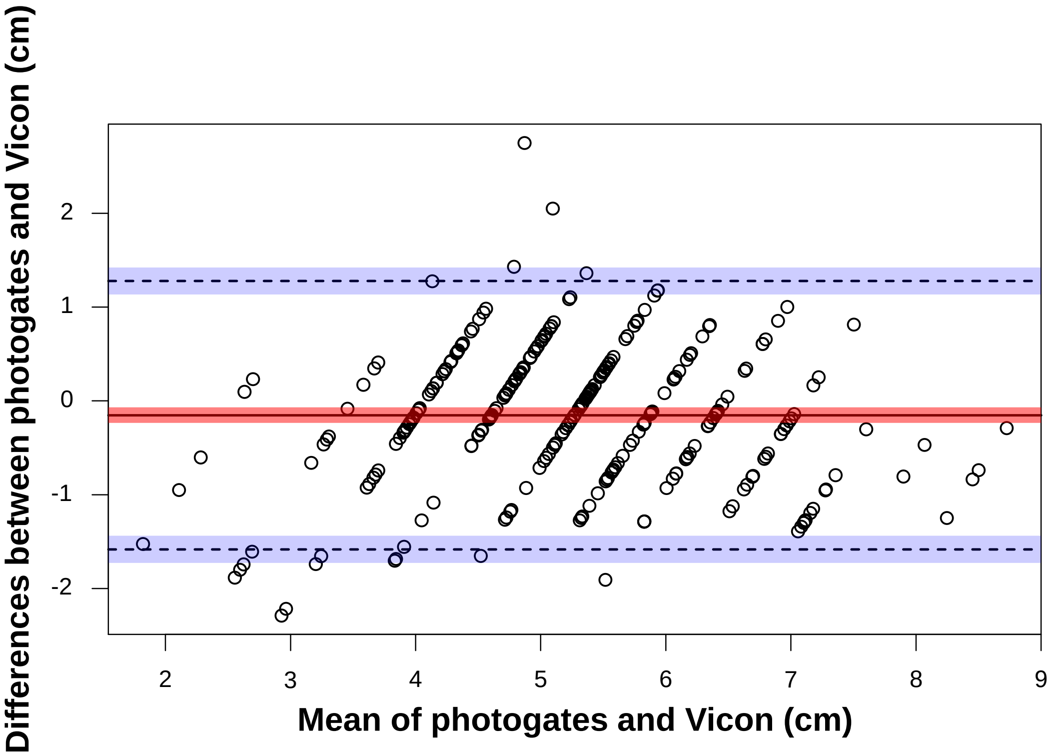


Figure 5.3 Bland-Altman plot representing the mean (x axis) and differences (y axis) of foot clearances measured by Vicon and the photogates. Limits of agreement are indicated as dotted lines with 95% confidence intervals (blue shading). The bias is represented as a solid line with 95% confidence intervals (red shading).

5.4 Discussion

This report demonstrates the first use of a novel photogate setup that shows very good accuracy and a very strong correlation to an optoelectronic system for measuring vertical foot clearances over a single step during stair ascent.

The results through our single marker height measurements show that the photogate setup is valid for measuring vertical height at step edge crossing. When foot clearance was measured, the photogates were also very accurate, however this was accompanied with a wider range of agreement. The range of agreement difference between the single marker height measurements and the foot clearance measurements highlights a significant complexity in the extraction of foot clearance height, which could be related to the virtual marker used for the foot clearance measurement (Vicon) and the time window used for extracting the lowest photogate broken. The ground truth for foot clearance was based upon the Vicon measurement of a single virtual marker at step edge crossing though importantly the first photogates broken may not have been caused by the aspect of the foot where the virtual marker is located (most anterior inferior aspect) due to how the foot may have been orientated at step edge crossing.

This could have led to measurement discrepancies between the two systems. The time window used for extracting the lowest photogate broken (0.0083 seconds from the first photogate breaking) might have partially ameliorated this, but importantly this window length may not have always captured the time at which the shoe aspect where the virtual marker is located breaks a photogate, especially for slower foot trajectories. Depending on the foot orientation, the virtual marker at such a time point may also not represent the lowest shoe aspect that broke the lowest photogate. For the single marker height measurements, the lowest photogate across all photogates broken (no time window) was extracted as the marker height and led to both a very accurate and precise photogate measurement. This approach could not be applied to the foot clearance trials as following the point of step edge clearance, the foot continues to travel downwards towards the step for foot placement and resultingly breaks all the lower photogates. The time window of photogate measurements helped to separate the foot to step edge clearance from the rest of the foot travel period.

The confounds above could be overcome through multiple virtual markers that cover a larger surface area of the shoe (Telonio et al., 2013). This would help in identifying the shoe aspect that crosses the step edge first for the measurements of foot clearance through Vicon and could lead to a better agreement range between the two systems. This will also help to determine whether an alternative approach of extracting the foot clearance measurement from the photogates may be needed but importantly the approach used in this study still resulted in very good measurement accuracy from the photogates.

The agreement in measured marker height may be further improved by correcting for the marker size used. Although good accuracy and precision were found for this measurement, the height captured by the photogates likely reflects the bottom marker aspect. Marker positions through Vicon are defined at the centre of the marker. This suggests potential offsets of around 0.7cm (radius of marker) between the two systems which is greater than the photogate spatial resolution (0.6cm). This potential source of error could be mitigated through the use of smaller markers. Further improvements to the photogates may include modifications to design features such as the state change (indicated by the falling edge detection) on the GPIO connections. The state change operates on the level of voltage surpassing a threshold and the voltage changes as a function of the light intensity on the phototransistor. The Raspberry Pi board cannot read analogue signals directly meaning it was not possible to determine whether some phototransistors were closer to a state change than others based on receiving more/less light. This could mean for some phototransistors more/less of the light would need to be broken for a change to be registered. This could be resolved by adding analogue to digital converters to each phototransistor channel which would provide voltage values and help indicate how close each phototransistor was to this threshold. Additional improvements may also include increasing the spatial resolution. This study used a resolution of ~0.6 cm for the photogates, whilst optoelectronic systems are capable of resolutions of ~0.1 cm (Merriaux et al., 2017). Increases to the spatial resolution could be achieved by reducing the housing diameter on the laser diodes, though clearly there will be a space limit on how many photogates can ultimately be setup.

The very small bias between the measurement systems suggests the photogate setup has good potential as an alternative to optoelectronic systems for measuring foot clearance. Foot to step edge clearance heights of 0.5 cm and below have been suggested as dangerous (Hamel et al., 2005b), meaning 0.5 cm could be considered a benchmark of the precision required for real word stair applications. The photogates have the additional advantage of being placed onto stairs as opposed to a participant whilst still providing accurate measurements. When compared to the previous studies our photogate setup shows greater accuracy (mean difference of -0.15cm) compared to the use of inertial measurement units (0.74cm error; (Benoussaad et al., 2016)) and 2D cameras (4.5cm error (Zult et al., 2019)). Previous measures of foot clearance also require instrumentation to be placed on the shoe sole or ankle (Benoussaad et al., 2016; Selvaraj et al., 2018). Having the instrumentation placed on stairs instead of an individual means stair movement is less likely to be restricted and could be a potential solution towards understanding better how stair falls occur in real world environments.

A current limitation of the photogate system involves the manual affixation and alignment of the lasers to the phototransistors, which can be time consuming. This may be overcome through permanent fixings and 3D printing solutions. The existing design of the device is also cumbersome and distracting to stair users. Converting this prototype into a professional, robust, and compact product that can be placed repeatedly on public stairs for prolonged time periods is highly desirable for future implementation. With an improvement to the factors outlined above this photogate setup has the potential to offer a simple and more portable solution for measuring stair foot clearance without the need for an optoelectronic system and could be further adapted to measure foot clearance during stair ascent and/or descent or over floor-based obstacles through similar design principles. This foot clearance setup would be particularly useful for measuring the impact of the previously developed stair HV illusions (Foster et al., 2015; Skervin et al., 2021) on public steps/stairs outside the confines of a laboratory environment.

5.5 Conclusion

This study demonstrates that a novel prototype photogate setup is valid for measuring vertical height over a step edge and has good accuracy for measuring stair foot clearance when compared to an optoelectronic system. Further improvements to the agreement range will likely require inclusion of multiple virtual markers on the surface of the foot and modifications to design factors. Addressing these limitations will contribute towards converting this prototype into a complete system that can provide an alternative to optoelectronic systems for measuring foot clearances outside of the laboratory environment.

Chapter 6: General discussion

6.1 Thesis aims

The main aim of this thesis was to determine whether modified stair HV illusions can be used on stairs to help improve older adult stair safety. The secondary aim was to create and test an alternative method capable of measuring foot clearance on stairs outside of a laboratory environment. This thesis overall showed that modified stair HV illusions do lead to safer stepping behaviours in older adults during stair ascent and that a custom-built photogate setup can accurately measure stair foot clearance when compared to an optoelectronic system with current limitations to the precision.

6.2 Summary of findings

To achieve the aims outlined above, this programme of work included a combination of psychophysical experimentation, biomechanical assessments, and electrical engineering to show that:

1. Modified stair HV illusions lead to increases in the perceived step riser height in older adults, as well as young adults.
2. A perception-action link exists in older adults between increased perceived riser heights and foot clearances in response to modified stair HV illusions at no disruption to other stair safety measures.
3. A modified stair HV illusion increases foot clearance over an inconsistently taller stair riser.
4. Photogates can accurately measure stair ascent foot clearance when compared to an optoelectronic system, however the photogates are currently limited by their precision.

Investigations began by modifying the design of previously used stair HV illusions with an appearance more suitable for older adult vision, those with photosensitivity to striped patterns and for a better aesthetic on public/home stairs. To achieve this, psychophysical experimentation was performed (chapter 2) to test designs reduced in spatial frequency and modified in mark space ratios. The main finding was that increases to the perceived riser heights in older and young adults were found despite the changes to the illusion design. No differences were noted between the different designs indicating that design modifications were possible with no consequence caused to the illusory effect of the stair HV illusion. To determine whether the increased perceived riser heights from the modified stair HV illusions were linked to increased foot clearances in older adults (perception-action link), modified stair HV illusions were placed onto the first and last step of a seven-step staircase to assess foot clearances, perceived riser height and other typical stair safety measures (Chapter 3). Increases in perceived riser heights and foot clearance were found in older and young adults in response to modified stair HV illusions indicating a perception-action link. This link was present at no detriment to other stair safety measures. The perception-action link was found to be stronger with the design that had a 70-30% mark space ratio. This design was further tested on an inconsistently taller mid-stair riser which is a common hazard known to reduce foot clearances due to the step height change going perceptually unnoticed (Chapter 4). When placed onto an inconsistently taller stair riser, the modified stair HV illusion increases foot clearance thereby offsetting the reduction in foot clearance that inconsistently taller risers usually cause. The modified stair HV illusion caused no detrimental changes to stair safety measures on the superimposed step. Lastly, a novel photogate setup was developed that measures stair foot clearance and was found to have good accuracy (small mean difference) when compared to an optoelectronic system (Vicon) though the range of agreement may be further improved through a greater number of foot virtual markers and/or adjustments to how foot clearance is extracted through the photogates.

6.3 Preventing stair falls with modified stair HV illusions

The increases in perceived riser height and foot clearance (perception-action link) show that the use of a modified stair HV illusion can be used as an effective visual cue to help improve stair safety. Whilst this thesis primarily aimed to improve stair safety for older adults, we also demonstrated the stair safety benefit of modified stair HV illusions in young adults. Dangerous levels of foot clearance are reported when they are within 0.5cm of the step edge (Hamel et al., 2005b). The foot clearance increases induced from the modified stair HV illusions across our experimental chapters are therefore relatively large, particularly for older adults who showed the largest increase in foot clearance (up to 2.1cm). When compared to other visual cues the increases in stair ascent foot clearance caused by a modified stair HV illusion appears to be more effective. Foster et al. (2015) showed no significant difference in foot clearance over a single step with an edge highlighter (7.1 ± 2.0 cm) compared to a plain step (6.9 ± 2.0 cm). Rhea, Rietdyk and Haddad (2010) showed large increases in toe elevation of 2.7cm when using a visual cue described as full (entire surface obstacle covered with glow in the dark tape) on an obstacle. However, over repeated trials the foot clearance effect of the full visual cue appears to reduce likely due to somatosensory adaptation (reduced from 2.7cm to 0.6cm increase in toe elevation). The findings in this thesis show that modified stair HV illusions remain effective despite the stair somatosensory influence. This shows that modified stair HV illusions may be a favourable option for helping to prevent stair falls when compared to other visual cues that have been tested.

Whilst the primary aim of the illusion was to increase foot clearance during stair ascent, falls also occur frequently during stair descent (Startzell et al., 2000) though for both circumstances a modified stair HV illusion will likely be a useful visual cue to help prevent a fall. The additional benefit of all modified stair HV illusions we tested is that they incorporate an edge highlighter in their designs. During stair descent, edge highlighters help to increase foot clearance and lead to more stable positions when stepping down (Simoneau et al., 1991; Zietz, Johannsen and Hollands, 2011; Foster et al., 2014; Thomas et al., 2021). This means that the modified stair HV illusion designs would provide a stair safety benefit for both stair ascent as well as stair descent. Whilst an edge highlighter has been found to be effective for stair descent, there may still be a potential benefit for developing a form of the stair HV illusion for stair descent in the presence of inconsistently longer treads. As with inconsistently taller risers, an inconsistently longer tread could also lead to reduced foot clearances due to the inconsistency going visually unnoticed. A stair tread illusion that increases perceived tread length could then lead to increases in foot clearances that offset the inconsistency. This should be confirmed through testing however as Francksen (2020) interestingly showed participants do adapt their foot contact length on a stair tread that is inconsistently shorter than the rest when compared to consistent treads, despite participants being unable to correctly identify the inconsistency post stair descent.

6.4 The perception-action link in response to modified stair HV illusions

The evidence that indicates a perception-action link in older adults in response to the modified stair HV illusions means these visual cues can be placed onto stairs with greater confidence that the change in perceived riser height will lead to an increased foot clearance and ultimately safer step edge crossing. This is important as changes in visual perception caused by illusions do not always lead to changes in action. This is explained by the two visual streams hypothesis, which suggests vision for action and vision for perception are processed through two different visual streams in the brain (ventral and dorsal visual streams). Although a degree of interaction between the two streams is recognised to exist (Milner and Goodale, 2008). Reasons why foot clearance corresponds to an increased perceived riser height across our experimental chapters could be due to when visual information is acquired about steps during normal stair walking. Previous findings indicate that visual information about a step is acquired in a feed forward manner (approximately 2 or 3 steps away) (Zietz and Hollands, 2009). This means that at the time of step edge crossing, participants are relying on visual memory of the step superimposed with the illusion. Previous findings indicate actions correspond more to perception when the action is performed from visual memory (Aglioti, DeSouza and Goodale, 1995; Gentilucci et al., 1996; Otto-de Haart, Carey and Milne, 1999). The stair HV illusion that was shown to have the strongest perception-action link was our 70-30% mark space ratio design with a spatial frequency of twelve cycles. This was evidenced in chapter 3 against the other modified stair HV illusions. Chapter 4 further confirmed the perception-action link with the 70-30% mark space ratio design over an inconsistently taller stair riser. On public stairs where a notable history of falls has been identified, or on stairs where an inconsistently taller step is unlikely to be visually perceived, the 70-30% mark space ratio design would likely be most suited for these circumstances. For an older adult, visually detecting such stair inconsistencies becomes even more unlikely due to age related losses in vision. This age-related decline in vision was evidenced across our vision-based tests. Even in the less likely circumstance where an individual does not perceive such steps to be taller with a modified stair HV illusion, the salient striped feature of the design and edge highlighter provide visual information about the step height.

Importantly, the modified stair HV illusions have minimal disruption to other measures of stair ascent safety. On steps with the illusion superimposed, no detrimental changes to stability or foot overhang were found across our experimental chapters, though in Chapter 4 there was an unexpected increase in anterior margins of stability on the step prior to the illusion. Whilst this might be related to a more forward leaning upper body posture and head flexion to visually focus on the step with the HV illusion, this was not the case in Chapter 3 whereby the illusion was placed on the first and last step. This means the change in stability could also be influenced by the step the illusion is placed upon.

6.5 Efficacy of the HV illusion with high-risk fallers

This thesis has demonstrated how modified stair HV illusions can help improve stair safety for older adults who are generally known to be at risk for stair falls, though it remains unknown whether the modified stair HV illusions would be effective with older adults who are identified to be at high fall risk. This could include older adults with low vision or those that may present neurological/physical impairments (Prevention and Panel, 2001) (such as individuals with Parkinson’s disease, or a history of stroke). The modified stair HV illusions have high contrasting features which enhance its visual saliency, meaning the illusions could provide useful visual information to those with significant visual loss and for individuals with Parkinson’s disease where disturbances to vision is a common symptom (Archibald et al., 2011; Urwyler et al., 2014). Falls in individuals with Parkinson’s disease is a significant issue and a high proportion of which are caused by a trip or slip (Gazibara et al., 2014). This has been reflected experimentally by low foot clearances during a gait task (Alcock et al., 2016). Recent findings by Alcock et al. (2020) show an improved visuomotor response (increased feedforward visual scanning and increased approach speed) in individuals with Parkinson’s disease when a high contrast obstacle is used compared to a low contrast during an obstacle crossing task. This suggests individuals with Parkinson’s disease could positively respond to modified stair HV illusions which is characterised by high contrasting features. However, disturbances to visual function in individuals with Parkinson’s disease include difficulty with judging objects and distances (Archibald et al., 2011; Urwyler et al., 2014) meaning the benefit of the modified stair HV illusion might be limited to its greater saliency as opposed to causing increases in perceived riser heights. Specific investigations are needed to determine whether the stair HV illusion could be effective with other populations such as those with dementia, those who have experienced stroke or children. Visual information about stair steps is usually performed in a feedforward manner (approximately 2-3 steps in advance, (Zietz and Hollands, 2009)) meaning visual memory of the step heights is likely used when crossing a step superimposed with a stair HV illusion. Individuals with dementia show reduced ability in visual memory recall when compared to unaffected controls (Flicker et al., 1984) meaning the stair HV illusion might not be as effective with this population. Individuals that have experienced a stroke have been shown to adopt more frontal plane compensatory strategies such as circumduction and hiking at the hip to achieve foot clearance during walking due to reduced knee and ankle dorsiflexion (Stanhope et al., 2014). Increasing the perceived height with a stair HV illusion may increase such circumduction to thereby increase the foot clearance on stairs, though this could lead to increased mediolateral instability. As with adults, studies assessing perception-action links in children also show inconsistent findings. One study showed children to perceptually respond to the Ebbinghaus illusion, but display a maximum grip aperture of the target circle(s) incongruent to the perception (Hanisch, Konczak and Dohle, 2001) whilst Duemmler et al. (2008) showed maximum grip aperture matches the perceptual response in children. These factors mean it is ultimately not clear how effective a stair HV illusion may be with such groups.

6.6 The next steps

This thesis was able to demonstrate that modified stair HV illusions help to improve older adult stair safety. To determine their effectiveness at reducing stair falls, modified stair HV illusions should be tested on stairs outside of the laboratory environment. The benefits of the stair HV illusion have been demonstrated in a controlled laboratory environment, but this may not reflect conditions found on real world stairs. For example, participants were secured into a fall safety harness and handrails were available and within arm’s reach meaning the participants may have perceived the stair fall risk to be small or less reflective of the increased risk on real world stairs. The laboratory staircase also did not have side walls (commonly found on real world stairs) along the stairs meaning other task irrelevant features were within a stair user’s visual field which might have influenced visual attention towards the illusion and/or stairs. On real world stairs, multiple individuals can be on a staircase at once which could interfere with how a stair user is able to visually attend to and perceive the illusion. These factors could influence the effectiveness of the illusion on real world stairs. Demonstrating increased foot clearances in response to the illusion on real world stairs would also help to provide more direct evidence of the stair safety benefit and would help strengthen recommendations related to future building regulations. The accuracy of the photogates reported in this thesis demonstrates the good potential such a setup has for measuring foot clearance on real world stairs. This is important as the setup requirements of other typical measurement methods restrict their use for real world stair assessments. The photogate setup could allow the possibility of collecting large amounts of foot clearance data over short time periods to assess how trip risk or stair falls change over time with the intervention of a modified stair HV illusion. This would be particularly relevant on stairs where there is a known history of falls or significant trip risk (such as inconsistently taller risers) or on stairs in the homes of those who have been identified at high risk of falling. Importantly future work should explore the acceptance for modified stair HV illusions to be implemented in homes or on public stairs. Where home modifications (such as the addition of edge highlighters on steps, handrails and more) have been accepted in a previous study rate of fall injuries at home reduced by 26% (Keall et al., 2015). These applications would also allow investigations as to whether repeated exposure to modified stair HV illusions over long periods of time reduces the foot clearance effect. Alongside stair assessments the photogate setup could be used to assess whether the modified stair HV illusions can be effective on raised surfaces in real world environments such as on kerbs, obstacles, or single steps. For implementation on public stairs, the modified stair HV illusion could be added onto steps where there is already an edge highlighter abutting the step edge, by adding the vertical stripes onto the stair riser aspect. Importantly however not all edge highlighters appear black as tested in this thesis. It is likely that some effect will still be present by the addition of vertical stripes onto the riser aspect of a step that already has an edge highlighter as a perceptual effect has still been demonstrated with vertical stripes alone (Foster et al., 2015). It is less clear however whether an edge highlighter with a different colour/contrast will still contribute to or maximise (Foster et al., 2015) the perceptual effect.

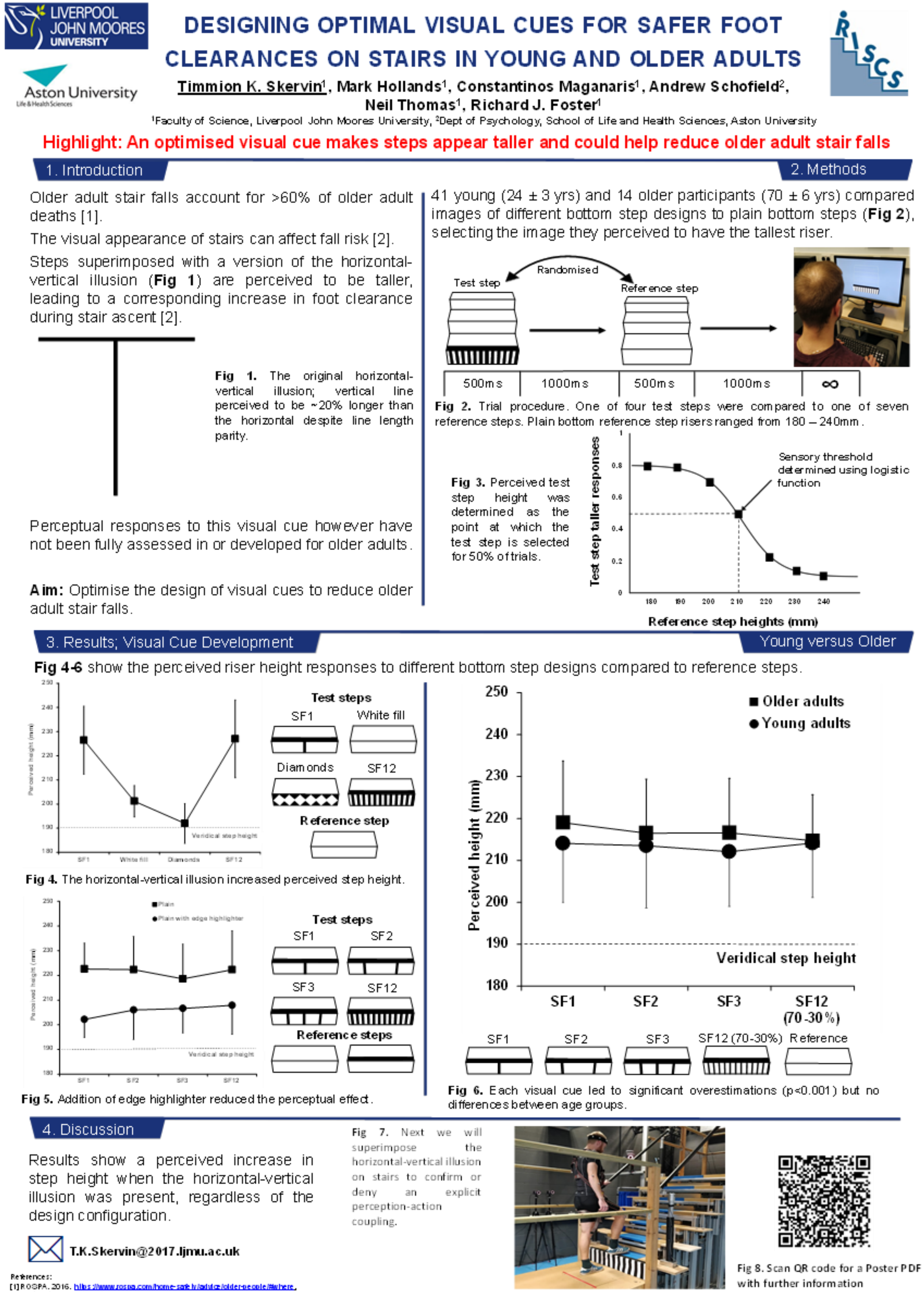
6.7 Conclusion

This thesis aimed to determine whether modified stair HV illusions can be used on stairs to help improve older adult stair safety. The secondary aim was to create and test an alternative method capable of measuring foot clearance on stairs outside of a laboratory environment.

This work has shown evidence for a perception-action link between increased perceived riser heights and foot clearance in older adults in response to modified stair horizontal-vertical illusions. The illusion is effective in addressing a common cause of stair falls and is a useful solution for the trip risk associated with inconsistently taller risers. The creation of a new photogate setup which has good accuracy when compared to an optoelectronic system could be used in future investigations to assess the use of the illusions on stairs or raised surfaces outside of the laboratory. Future investigations should further test the effectiveness of the illusions with older adults identified at high risk for falls and explore the feasibility of implementation in public/real world environments.

Appendices

Appendix A: Award winning poster at the British Association of Sport and Exercise Sciences (BASES), Biomechanics Interest Group (BIG) conference 2019



DESIGNING OPTIMAL VISUAL CUES FOR SAFER FOOT CLEARANCES ON STAIRS IN YOUNG AND OLDER ADULTS

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Highlight: An optimised visual cue makes steps appear taller and could help reduce older adult stair falls

1. Introduction

Older adult stair falls account for >60% of older adult deaths [1].

The visual appearance of stairs can affect fall risk [2].

Steps superimposed with a version of the horizontal-vertical illusion (**Fig 1**) are perceived to be taller, leading to a corresponding increase in foot clearance during stair ascent [2].

Fig 1. The original horizontal-vertical illusion; vertical line perceived to be ~20% longer than the horizontal despite line length parity.

Perceptual responses to this visual cue however have not been fully assessed in or developed for older adults.

Aim: Optimise the design of visual cues to reduce older adult stair falls.

2. Methods

41 young (24 ± 3 yrs) and 14 older participants (70 ± 6 yrs) compared images of different bottom step designs to plain bottom steps (**Fig 2**), selecting the image they perceived to have the tallest riser.

Fig 2. Trial procedure. One of four test steps were compared to one of seven reference steps. Plain bottom reference step risers ranged from 180 – 240mm.

Fig 3. Perceived test step height was determined as the point at which the test step is selected for 50% of trials.

3. Results; Visual Cue Development

Fig 4-6 show the perceived riser height responses to different bottom step designs compared to reference steps.

Fig 4. The horizontal-vertical illusion increased perceived step height.

Fig 5. Addition of edge highlighter reduced the perceptual effect.

Young versus Older

Fig 6. Each visual cue led to significant overestimations (p<0.001) but no differences between age groups.

4. Discussion

Results show a perceived increase in step height when the horizontal-vertical illusion was present, regardless of the design configuration.

Fig 7. Next we will superimpose the horizontal-vertical illusion on stairs to confirm or deny an explicit perception-action coupling.

Fig 8. Scan QR code for a Poster PDF with further information

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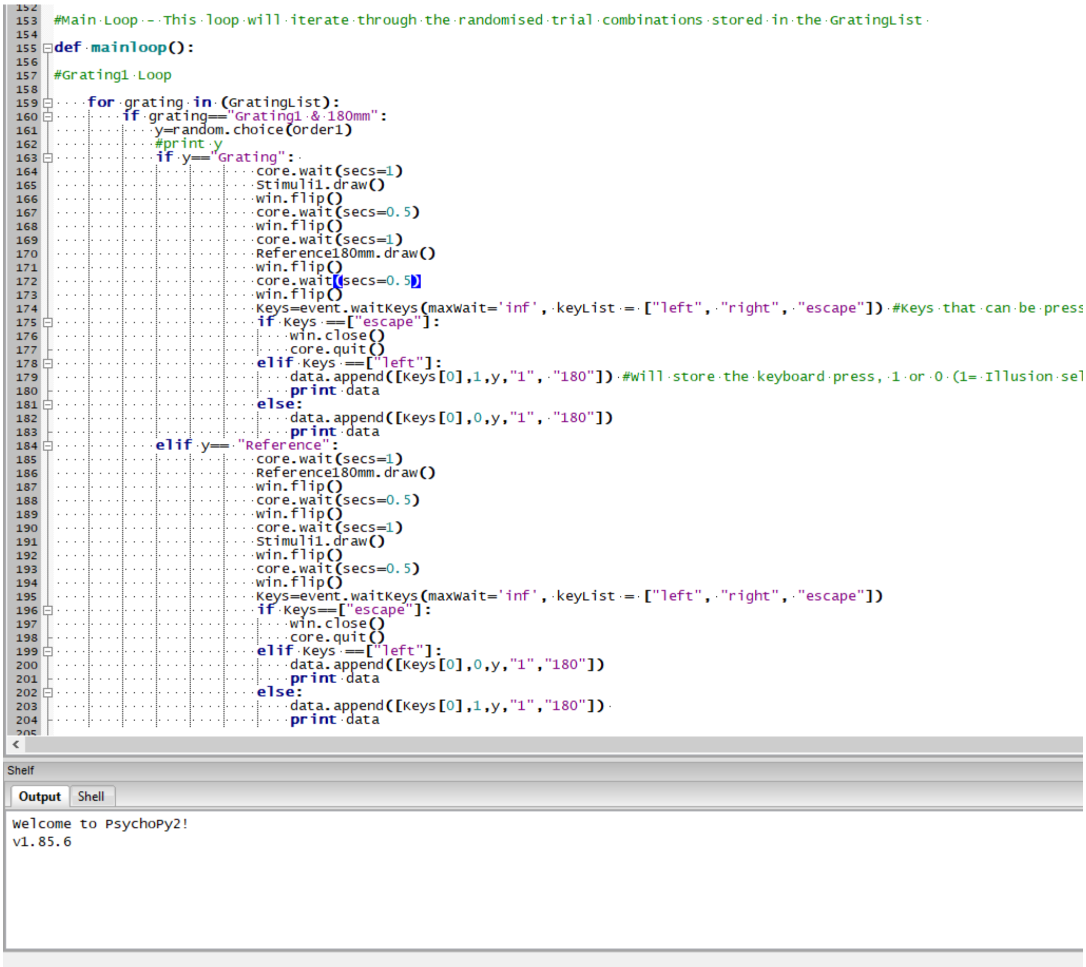
References:
[1] ROSPA. 2016. https://www.rospa.com/home-safety/advice/older-people/#where.
[2] Foster et al. Invest Ophthalmol Vis Sci, 2015.

Figure A.1 Poster presented at the British Association of Sport and Exercise Sciences (BASES), Biomechanics Interest Group (BIG) conference 2019.

Appendix B: Code snippet for the psychophysical experimentation

The code snippet below represents part of the main loop that was used to present randomised test and reference stimuli on screen. Participants' keyboard responses were recorded and appended to a list which was exported as a csv file at the termination of the test.



```
#Main Loop - This loop will iterate through the randomised trial combinations stored in the GratingList 

def mainloop():

#Grating1 Loop

    for grating in (GratingList):
        if grating=="Grating1 & 180mm":
            y=random.choice(Order1)
            #print y
            if y=="Grating": 
                        core.wait(secs=1)
                        Stimuli1.draw()
                        win.flip()
                        core.wait(secs=0.5)
                        win.flip()
                        core.wait(secs=1)
                        Reference180mm.draw()
                        win.flip()
                        core.wait(secs=0.5)
                        win.flip()
                        Keys=event.waitKeys(maxWait='inf', keyList = ["left", "right", "escape"]) #Keys that can be press
                        if Keys ==["escape"]:
                            win.close()
                            core.quit()
                        elif Keys ==["left"]:
                            data.append([Keys[0],1,y,"1", "180"]) #Will store the keyboard press, 1 or 0 (1= Illusion sel
                            print data
                        else:
                            data.append([Keys[0],0,y,"1", "180"])
                            print data
            elif y== "Reference":
                        core.wait(secs=1)
                        Reference180mm.draw()
                        win.flip()
                        core.wait(secs=0.5)
                        win.flip()
                        core.wait(secs=1)
                        Stimuli1.draw()
                        win.flip()
                        core.wait(secs=0.5)
                        win.flip()
                        Keys=event.waitKeys(maxWait='inf', keyList = ["left", "right", "escape"])
                        if Keys==["escape"]:
                            win.close()
                            core.quit()
                        elif Keys ==["left"]:
                            data.append([Keys[0],0,y,"1","180"])
                            print data
                        else:
                            data.append([Keys[0],1,y,"1","180"]) 
                            print data
```

```
Welcome to PsychoPy2!
v1.85.6
```

Figure B.1 Part of the code used for the psychophysical experimentation in chapter 2.

Appendix C: Published manuscript

The image below represents the front page of the recently published manuscript containing the findings from chapters 2 and 3.

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ELSEVIER

The next step in optimising the stair horizontal-vertical illusion: Does a perception-action link exist in older adults?

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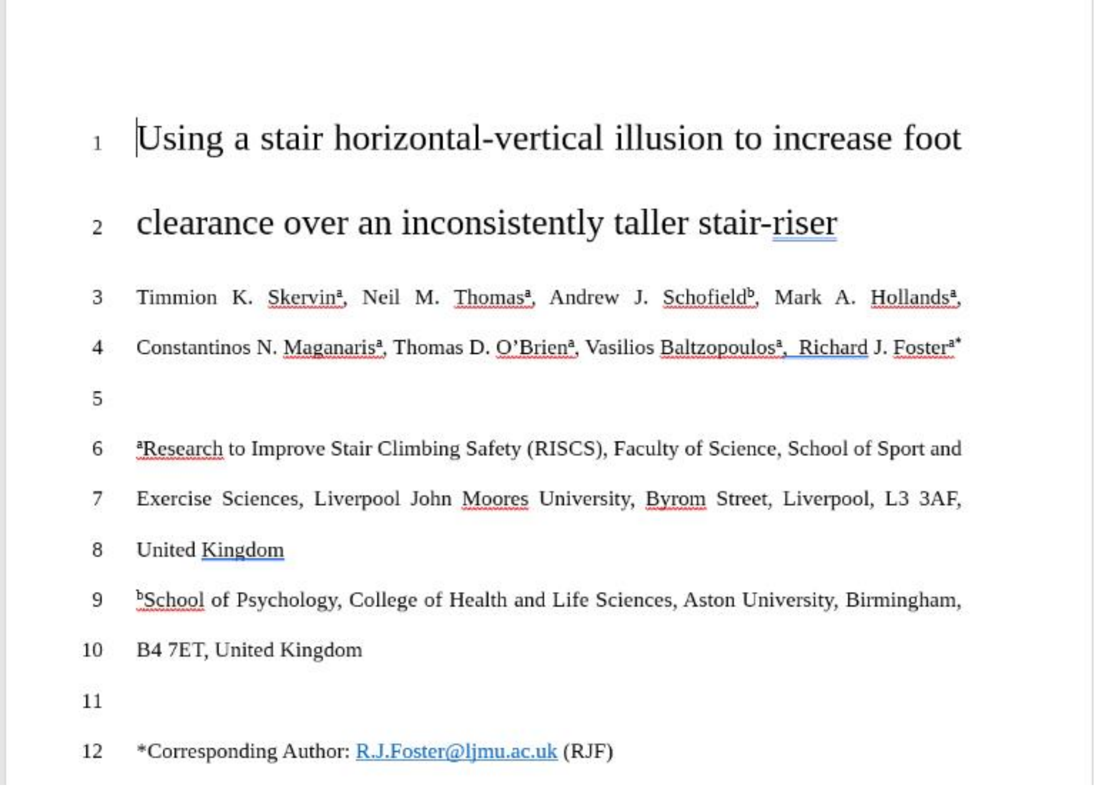
ABSTRACT

Introduction: Tripping on stairs results from insufficient foot to step edge clearance and can often lead to a fall in older adults. A stair horizontal-vertical illusion is suggested to increase the perceived riser height of a step and increase foot clearance when stepping up. However, this perception-action link has not been empirically determined in older adults. Previous findings suggesting a perception-action effect have also been limited to a single step or a three-step staircase. On larger staircases, somatosensory learning of step heights may be greater which could override the illusory effect on the top step. Furthermore, the striped nature of the existing stair horizontal-vertical illusion is associated with visual stress and may not be aesthetically suitable for use on public stairs. These issues need resolving before potential future implementation on public stairs.
Methods: Experiment 1. A series of four computer-based perception tests were conducted in older ($N = 14$: 70 ± 6 years) and young adults ($N = 42$: 24 ± 3 years) to test the influence of different illusion designs on stair riser height estimation. Participants compared images of stairs, with horizontal-vertical illusions or arbitrary designs on the bottom step, to a plain stair with different bottom step riser heights and selected the stair they perceived to have the tallest bottom riser. Horizontal-vertical illusions included a previously developed design and versions with modified spatial frequencies and mark space ratios. Perceived riser height differences were assessed between designs and between age groups. *Experiment 2.* To assess the perception-action link, sixteen older (70 ± 7 years) and fifteen young (24 ± 3 years) adults ascended a seven-step staircase with and without horizontal-vertical illusions tested in experiment 1 placed onto steps one and seven. Foot clearances were measured over each step. To determine whether changes in perception were linked to changes in foot clearance, perceived riser heights for each horizontal-vertical illusion were assessed using the perception test from experiment 1 before and after stair ascent. Additional measures to characterise stair safety included vertical foot clearance, margins of stability, foot overhang, stair speed, and gaze duration, which were assessed over all seven steps.
Results: Experiment 1. All horizontal-vertical illusion designs led to significant increases in the perceived riser height in both young and older adults (12–19% increase) with no differences between age groups. *Experiment 2.* On step 7, each horizontal-vertical illusion led to an increase in vertical foot clearance for young (up to 0.8 cm) and older adults (up to 2.1 cm). On step 1 significant increases in vertical foot clearance were found for a single horizontal-vertical illusion when compared to plain (1.19 cm increase). The horizontal-vertical illusions caused significant increases in the perceived riser height (young; 13% increase, older; 11% increase) with no differences between illusion design, group or before and after stair ascent. No further differences were found for the remaining variables and steps.
Conclusion: Results indicate a perception-action link between perceived riser height and vertical foot clearance in response to modified versions of the horizontal-vertical illusion in both young and older adults. This was shown

Figure C.1 Published manuscript entitled 'The next step in optimising the stair horizontal-vertical illusion: Does a perception-action link exist in older adults?

Appendix D: Abstract for the award-winning free communication at the British Association of Sport and Exercise Sciences (BASES), Biomechanics Interest Group (BIG) conference 2021



Using a stair horizontal-vertical illusion to increase foot clearance over an inconsistently taller stair-riser

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Figure D.1 Abstract submitted to BASES BIG 2021 conference, presented as a free communication (oral presentation).

Appendix E: Corrected and uncorrected post hoc statistical tests

Below is a table showing the corrected and uncorrected post hoc statistical tests for the margin of stability comparisons on step 6 in chapter 4, whereby significance was found through a repeated measures ANOVA however the Bonferroni post hoc corrections did not reach statistical significance.

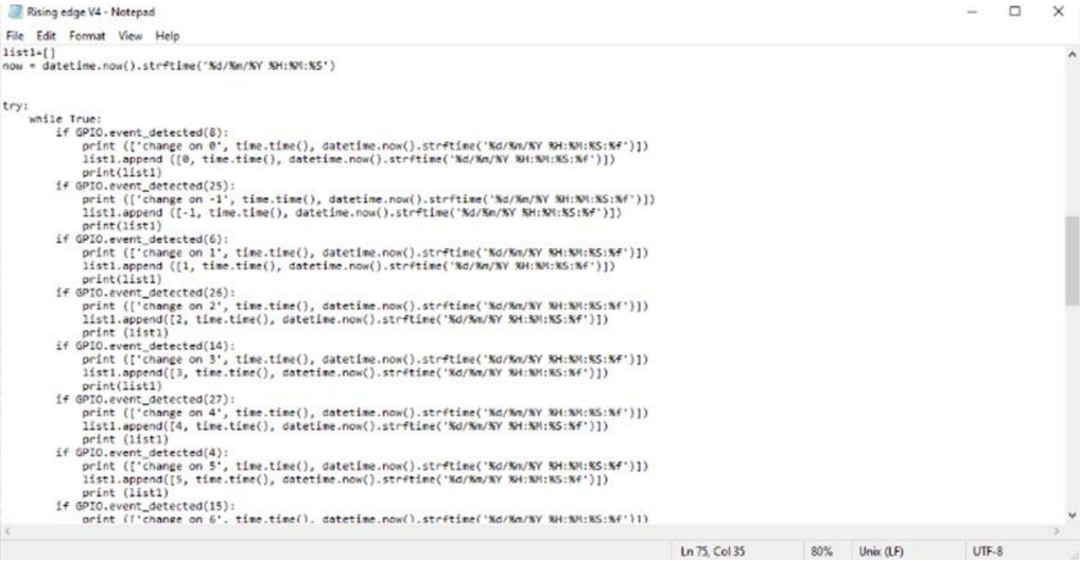
Table E.1 Bonferroni corrected and uncorrected post hoc statistical tests for margins of stability on step 6.

Step 6 anteroposterior margin of stability		
	Bonferroni corrected post hoc	**Uncorrected post hoc**
Illusion vs inconsistent	*p*=.196	*p*=.065
Consistent vs inconsistent	*p*=.111	*p*=.037
Illusion vs consistent	*p*=.775	*p*=.258
Step 6 mediolateral margin of stability		
Illusion vs inconsistent	*p*=.054	*p*=.018
Consistent vs inconsistent	*p*=.066	*p*=.022
Illusion vs consistent	*p=1*.000	*p*=.636

Statistical significance achieved through uncorrected post hoc's are shaded in grey.

Appendix F: Code snippet for programming of photogates

The code snippet below represents part of the main loop that was used to program the photogates. This code continually listens for a change in voltage across the GPIO pins which occurs when the photogate beam is broken. Time stamps are generated at the instant the photogate(s) are broken. This information alongside the specific photogate broken is then stored into a list and exported as a text file.



```
list1=[]
now = datetime.now().strftime('%d/%m/%Y %H:%M:%S')


try:
    while True:
        if GPIO.event_detected(8):
            print (['change on 0', time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
            list1.append ([0, time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
            print(list1)
        if GPIO.event_detected(25):
            print (['change on -1', time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
            list1.append ([-1, time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
            print(list1)
        if GPIO.event_detected(6):
            print (['change on 1', time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
            list1.append ([1, time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
            print(list1)
        if GPIO.event_detected(26):
            print (['change on 2', time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
            list1.append([2, time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
            print (list1)
        if GPIO.event_detected(14):
            print (['change on 3', time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
            list1.append([3, time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
            print(list1)
        if GPIO.event_detected(27):
            print (['change on 4', time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
            list1.append([4, time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
            print (list1)
        if GPIO.event_detected(4):
            print (['change on 5', time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
            list1.append([5, time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
            print (list1)
        if GPIO.event_detected(15):
            print (['change on 6', time.time(), datetime.now().strftime('%d/%m/%Y %H:%M:%S:%f')])
```

Figure F.1 Code snippet for the programming of photogates

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