Use of Gaze and Gait Analysis to Assess the Effect of Footway Environmental Factors on Older Pedestrians' Accessibility

Thesis submitted to University College London for the degree of Doctorate of Philosophy

Tsu-Jui Cheng

Department of Civil, Environmental & Geomatic Engineering

2014

I, Tsu-Jui Cheng, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

Walking in the footway environment is an essential activity of daily living and the physical activity associated can also improve an individual's quality of life. The possibility and ability for the individual to reach opportunities and participate in activities on foot indicate the accessibility of the footway environment. One of the major hazards in the footway environment that impedes the accessibility is falling. While it may happen to anyone, falling is more common in older people and the consequence of falling could seriously deteriorate their quality of life.

Falls among older people is one of the major public health problems. Fall-induced injuries, either physical or psychological, can lead to further physical frailty and social isolation. Although falls study on the elderly has been widely discussed, there is little information available on risk factors in the outdoor footway environment. The current guidance of design and condition of footway environment, however, is short of scientific justification. The potential hazard of a single step-height, such as defects and kerbs on the pavement, is commonly encountered as well as negotiated by the individual under different lighting conditions. Therefore, a framework within which the interaction among sensory and physical capability and environmental factors could be well investigated is needed.

This thesis investigates the process of planning for negotiating upcoming step-heights on the pavement, and aims at establishing changes in gaze (where people look) and gait (how people walk) behaviour in relation to combinations of environmental factors such as step-heights and lighting levels. About 17 young (aged 25-34) and 17 older (aged 65-74) participants walked on a straight walkway with 16 experimental conditions (8 step-heights at 2 lighting levels, one step-height in each environmental setting), and the visual and walking patterns were collected.

The results demonstrated the inconspicuous descending step-heights (due to a lack of visibility) as well as the lower lighting level demanded additional visual attention and additional time to plan footsteps. Step-height of ±60 mm was found to be the threshold of sensory as well as physical capability, which should be considered as suggested guideline for pavement design. Both ±125 and ±30 mm were perceived as

more dangerous due in part to additional body function requirement and the nature of visual ambiguity respectively.

More importantly, young participants demonstrated the agility and adaptability to different environmental setting whereas older people demonstrated more disturbed gait pattern and increased visual attention. Also, older people were more likely to face the risk of falling as they detected the step-heights later, had shorter time for response than young participants. Therefore in footway design, older people's perception as well as reaction to response to the footway environment should be considered and the pavement should be designed to accommodate their needs.

Bringing together the gaze and gait analysis is proved to be important in this thesis and it is essential for further research in understanding the cognitive process in between. The responses to risks of falling could not be understood without knowing the association between the visual perception and gait adjustments.

The approach developed in this thesis might be used to further analyse microscopic as well as macroscopic scales of accessibility of the footway environment and provide some insights into how the individual's sensory, cognitive and physical capability affect the decision making process while walking.

Acknowledgement

This thesis would not have been possible without enormous helps from many kind people and also this journey would not have been such a thrill.

Firstly I would like to thank my principal supervisor, Prof Nick Tyler, for his guidance and him always being supportive and inspiring. This PhD project would not have gone this far without his constant challenges and generous help. Working with Nick has been an extraordinary and unforgettable experience in a life time.

My sincere and massive thanks also go to my secondary supervisor, Dr Catherine Holloway, for her supervision and her always being there to offer tremendous help whenever there was a problem in this journey. I am grateful for having worked with Catherine on both my PhD project and PAMELA projects.

I have also received invaluable help with the data analysis from researchers within UCL. I would like to thank Dr Tatsuto Suzuki for his vast and comprehensive knowledge in biomechanical engineering and Matlab. The data analysis in this thesis would not have been completed without his help. My thanks also go to Dr Chien-Ju Lin then at the Department of Statistical Science at UCL and now at Cambridge MRC for her deep knowledge in the statistical analysis and her precious time outside her own research.

The pilot and main experiments of this thesis would not have been realised without the generous support from researchers and technicians at PAMELA. I would like to thank Dr Derrick Boampong, Dr Karen Hayrapetyan and Harry Rostron for their professional technical support.

My sincere thanks go to my colleagues at ARG. I would like to thank Dr Taku Fujiyama for his invaluable comments on this project as well as administrative support. Special thanks go to Dr Craig Childs, Dr Simrn Kaur Gill, Dr Emily Digges La Touche, Roselle Thoreau, Reka Solymosi, Xenia Karekla, Natalie Chan, Nikos Papadosifos, Kristy Revell, Kamal Achuthan, and Tianyu Wang for their help with my study and their broad knowledge in accessibility research.

Special thanks also go to Rhommel Go, the physiotherapist of Whittington Hospital, for introducing me to the balance training class for older people, in which I learned the knowledge in falls and ageing.

I would like to thank all of the 34 participants taking part in the experiments for their effort and time spent at PAMELA.

I am also very grateful to my officemates at CEGE who always generously shared knowledge in research in general: Dr Riccardo Scarinci, Dr Tom Cohen, Clemence Cavoli, Fang Xu, Adriana Ortegon, Hussam Nasreddin, Ran Chen and Shuai Li.

I would also like to thank my friends who gave me invaluable advice on research or help in life during my PhD study: Dr Jenny Roan, Dr Chia-Hsun Chang, Naomi Li, Nuo Duan, Ying Li, Chien-Pang Liu, Runing Ye and Joe Fan.

Also I would like to thank my parents Jung-Chen Cheng and Ta-Ling Wang for their tremendously invaluable support in the last few years. This PhD study would not even have started without their generous support, patience and understanding. Thanks also go to my sister Tsu-Pei Cheng for her support in the last few years and for her introducing UK to me 15 years ago.

Finally, I would like to thank Yinfang Wang for her incredible patience and consideration during the bumpiest period of this long journey. Thank you for being so supportive and believing in us.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

Walking in the footway environment is an essential activity of daily living and the associated physical activity can also improve an individual's quality of life. Walking, as a mode of transport, enables the individual to travel from one place to another in order to reach opportunities and participate in activities – every journey starts and includes a walking component. The possibility and ability for the individual to achieve goals indicate the accessibility of the integration between activities, environment and the individual's attributes. The accessibility of the footway environment, therefore, is fundamental to the individual's mobility as well as the quality of life. One of the major hazards in the footway environment that impedes accessibility is falling on the pavement. While it may happen to anyone, falling is more common in older people and the consequence of falling could seriously deteriorate their quality of life.

Falling is one of the major physical health problems in older people. About 2,300 people over 65 in the UK fall every day (Help the Aged, 2008a). These reported falls could be as minor as a 'near-miss' (where a person is able to regain their balance by means of some form of self-balancing mechanism or by making use of nearby external supports such as a chair or a wall), but could also be critical where the person is immobilised as a result of a fracture or other injury. Along with the physical injuries, older people might consequently suffer psychologically from falls so that they stop leaving their homes, further deteriorating their quality of life (Help the Aged, 2008b). In 2011, the National Osteoporosis Society estimated that £2.3 billion was spent on hospital and social care for patients with a hip fracture (National Osteoporosis Society, 2011) but as this estimation did not take the cost of non-fracture injuries, fracture injuries of other parts of the body or unreported falls incidents into account, the overall healthcare cost of falls is likely to be even higher. Despite the fact that older people have degenerating physical conditions which might stop them from going outdoors, they engage with streets on a regular basis by visiting local amenities such as shops and post office on foot (Burton and Mitchell, 2006). Therefore the condition of pavements is crucial for older pedestrians.

A survey in 2007 reported that 2.5 million people aged 65 and over have fallen to the ground due to uneven pavements (Help the Aged, 2007b). The request for a better pavement condition had been called for by approximately 22 per cent of the older people aged 65 and over who also thought better pavements could make their lives more active (Help the Aged, 2007a). In addition, Burton and Mitchell (2006) indicated that better maintained pavements have topped the list of improvement for the outdoor environment suggested among older people, and the I'DGO project (Inclusive Design for Getting Outdoors, 2007) stated that qualities of the pavement affect the quality of life in the elderly.

Previous literature provides extensive discussion and information on such walking behaviour as stepping and stair walking performance. However, the footway environmental factors are rarely considered and the correlation between the environmental factors and walking behaviour has not been fully understood. In addition, the importance of the condition of footway and pavement has been widely recognised but the feedback of the individual's sensory and physical capabilities has not been well investigated.

Local councils have realised the importance of pavement maintenance. Between 2006 and 2010, 226 out of the 431 local councils in the UK spent over £1 billion on repairs to pavement, kerbs and public walkways; however, more than £106 million was spent on compensation claims due to tripping or falling on the pavement (White and Kerridge, 2011). Sixty-six councils who responded to a survey in 2007 had between them budgeted £16.3 million for potential compensation claims for falls on broken kerbs, pavement or public walkways (Help the Aged, 2008a). Although well-maintained pavements have been called for by both of local authorities and communities, the definition of quality pavements has not been clearly investigated and the impacts of the footway environment on walking behaviour among older people have not been fully understood.

The current guidance for design and condition of the footway environment is short of scientific justification as well as consideration for the inclusion of older people (Department for Transport, 2007). Although the literature in obstacle detection (see

Section 2.4) and street lighting (see Section 2.3.3, 2.3.4 and 2.3.5) demonstrates a scientific approach to the optimal design of the footway, the current knowledge is based on the individual's self-reported perception in a static experimental environment. The individual's sensory as well as physical capabilities and the capabilities attached to environmental factors did not fully engage in the footway environment in previous research. Therefore, a framework within which the interaction between the individual's capability and environmental factors can be well investigated is needed.

The *Capability Model* developed by Cepolina and Tyler (2004) and further explained by Tyler (2006) provides a framework within which measurement of the individual's capability to navigate around and the environmental factors in the footway environment could be approached. Walking in the footway environment (*Activity*) is achieved by the interaction between the individual's sensory, cognitive and physical capabilities (*Provided Capabilities*) and the capabilities attached to the environment (*Required Capabilities*). The risk of falling and the fall incidents indicate that *Activity* is not achievable due to the mismatch between *Provided Capabilities* and *Required Capabilities* as the latter exceeds the former. As the consequence, the footway environment is not accessible to all.

Walking in the footway environment is an intrinsic yet intricate activity comprising a series of physical as well as psychological decisions and the impacts of the immediate environment. This thesis centres on key elements in the footway environment which require interaction with the individual's sensory and physical capabilities. The environmental factors attaching to *Required Capabilities* used within this thesis are lighting level and step-height (changes of levels on the pavement). The individual's sensory and physical capabilities representing *Provided Capabilities* are then taken to be gaze behaviour (how the individual perceives the information of the environmental factors) and gait pattern (how the individual plans footsteps while approaching the step-height). The key in this thesis is that these two capabilities need to be studied not only individually but also in combination in order to understand how the footway impacts on the individual's ability to walk along it. This has not been done before and constitutes a major challenge in the research environment.

1.1 Aim and composition of the thesis

The purpose of this thesis is to measure the correlation between environmental factors and the individual's capability in the footway environment. Older people's capability is the main focus of this thesis but in order to understand if the perception of footway environment is age-related, young people's capability is measured and serves as baseline performance. Research questions of this thesis will be detailed in Section 2.6.

This thesis comprises eight chapters.

Chapter 1: Introduction gives the overview of current issues and the aims and composition of this thesis.

Chapter 2: Background reviews the framework of the Capability Model and previous research in footway accessibility. Research questions are then detailed.

Chapter 3: Methodology explains the rationale of the methods and defines the parameters used in the experiments designed to measure the correlation between sensory as well as physical capabilities and environmental factors.

Chapter 4: Instrumentational Synchronisation Validation and Statistical Analysis reports the validation of the intrumentational synchronisation and the results of the statistical analysis.

Chapter 5: Results And Discussion On Gaze Behaviour explains the results of gaze performance of Chapter 4, along with the results of descriptive analysis.

Chapter 6: Results And Discussion On Gait Pattern explains the results of gait performance of Chapter 4, along with the results of descriptive analysis.

Chapter 7: Results And Discussion On The Interaction Between Gaze And Gait Variables And Implication For Footway Design explains the results of the interaction between gaze and gait performance of Chapter 5 and 6, along with the results of descriptive analysis, and then compares the overall results with current footway design guidance.

Chapter 8: Conclusion summaries the achievement of this thesis and suggests topics for further research emerging from the results and discussions in this thesis.

Chapter 2: Background

Chapter 1 has revealed the prevalence of falls on the pavement and the cost of aftermath medical treatments. The safety of walking in the footway environment is therefore of great importance, especially for older people. In order to understand the accessibility of the the footway environment, this chapter firstly reviews the *Capability Model* (Cepolina and Tyler, 2004; Tyler, 2006) used to unfold the elements of risk of falling in the footway environment (Section 2.1). Each element is then reviewed in the following sections: *Provided Capabilities* (Section 2.2), *Required Capabilities* (Section 2.3) and Walking in the built environment (Section 2.4).

In Section 2.2 *Provided Capabilities*, previous research in the physical and psychological characteristics of older people is reviewed (Section 2.2.1). In addition, definitions of a fall, a trip and stumbling are discussed and identified, followed by reviews of the factors of outdoor falls and the psychological consequence of falls - fear of falling (Section 2.2.2).

In Section 2.3 *Required Capabilities*, regulations about pavements in design guidelines as well as maintenance manual of pavements (Section 2.3.1) and building regulations (Section 2.3.2) are reviewed. Regulations and studies of street lighting in general (Section 2.3.3), lighting specifically for pedestrians (Section 2.3.4) and especially for older people (Section 2.3.5) are then described. Research in emergency lighting level for fire evacuation is also reviewed for providing the information about the absolute minimum lighting level (Section 2.3.6). The environmental interventions against risk of falling in the outdoor environment are then detailed (Section 2.3.7).

A person is using the footway because they seek to carry out some form of activity. Walking on the footway in the built environment is made up of a number of components, each of which has to be accessible if the activity is to be completed. Walking in the built environment is defined in Section 2.4 and then examples of person-environment interactions studied in previous studies in obstacle clearance (Section 2.4.1) and walking up and down stairs (Section 2.4.2) are reviewed. Detailed review of the sensory capabilities (gaze) (Section 2.4.3) and physical capabilities (gait) (Section 2.4.4) associated with different walking tasks is carried out. The coordination between sensory and physical responses in walking tasks is also reviewed (Section 2.4.5).

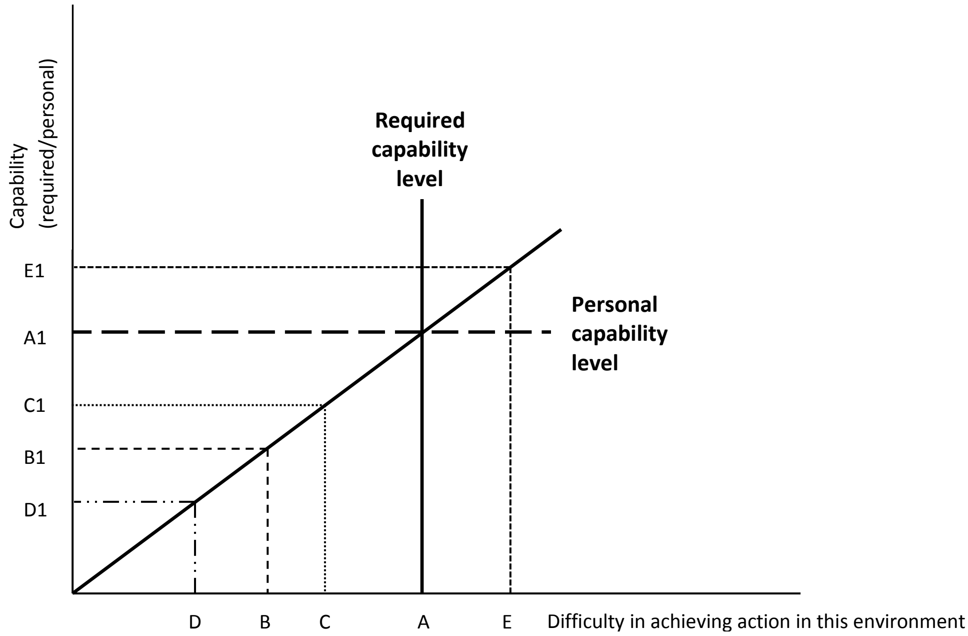
Finally, discussion and conclusion of this chapter are presented (Section 2.5) and the research questions are raised accordingly (Section 2.6).

2.1 Accessibility and Capability Model

Fall incidents and the cost of medical treatment as well as rehabilitation for fall-induced injuries show that the footway environment contains risks impeding the individual’s ability to negotiate the urban environment on foot, as stated in Chapter 1. This is especially true for older people; therefore the environment is not accessible for all. Halden and colleagues conducted a holistic literature review in accessibility analysis and defined physical accessibility barriers as ‘be[ing] classified in terms of the assistance which people require to make a journey using any particular mode’ (Halden et al., 2005). In order to measure the assistance individuals need to cope with physical accessibility barriers, it is essential to measure the inaccessibility and to understand what these barriers are.

The measurement of accessibility can be approached by understanding the capabilities at both ends of the process: individuals and environment. Cepolina and Tyler (2004) developed the *Capability Model* (See Figure 2-1) to explain the interactions between an individual, the environment and the activities the individual wishes to pursue (See Figure 2-2).

In the *Capability Model* (see Figure 2-1), the difficulty of achieving a particular task in a given environment is represented by the x-axis and the capabilities either provided by the individual or required by the environment by the y-axis. Each task has an associated level of difficulty or barriers (represented by D, B, C, A and E) in relation to the capability requirements (represented by D1, B1, C1, A1 and E1). Point A acts as the threshold of inaccessibility as the barriers become too difficult to negotiate. Therefore tasks beyond this threshold are impossible to achieve.



A: Point at which action become impossible (= “barrier”)
B: “Standard environment”
C, E: “current environment” in which it is harder than in the standard environment to achieve action
D: “current environment” in which it is easier than in the standard environment to achieve action
A1: Capability level required at A
B1: Capability level required to achieve success in the “standard environment” (= “capacity”)
C1, D1: Capability levels required in current environments C or D respectively to achieve action (“performance”)
E1: In this case the required capability level is greater than the personal capability level and the action would be impossible
“Performance gap” = B1 – [C1, D1 or E1]

Figure 2-1: Illustrative graph indicates the relationship between the individual’s capabilities and the difficulty in a given environment.
Modified from Cepolina and Tyler, 2004 and Tyler, 2006.

At the microscopic level, the provision of capabilities by the individual indicates the ability to achieve a body function in the given environment (x-axis) whereas the capability required by the environment indicates the capability needed to complete an activity (see Figure 2-2). The *Provided Capabilities* involve individuals’ sensory and physical capabilities such as vision, cognitive and biomechanical functions; the *Required Capabilities* reflect constraints imposed by the environment, such as pavement layouts and fellow pedestrians. The *Activity* is a target that needs to be achieved by the interaction between the *Provided* and *Required Capabilities*, and once the *Required Capabilities* exceed the *Provided Capabilities*, the activity will become unachievable (throughout this thesis, the term *Activity* in italic represents the activity defined in the *Capability Model*). It is quite common for the reason for the *Required*

Capabilities to become larger than the *Provided Capabilities* lies within the pedestrian environment and if this is the case, the environment where the activity takes place, or on the way to/from it, is inaccessible, thus rendering the activity inaccessible as well.

Tyler (2006) further explained the microscopic level of the *Capability Model* with the example of the footway environment. Passing a kerb on the pavement is a common activity for pedestrians; however, not all pedestrians are adaptive to encounter various kerb heights. In order to understand why some kerb heights are more achievable than others for some pedestrians and/or why some kerb heights are more achievable for some pedestrians than others, the interaction between kerb heights (*Required Capabilities*) and individuals' sensory and physical performance (*Provided Capabilities*) needs to be investigated.

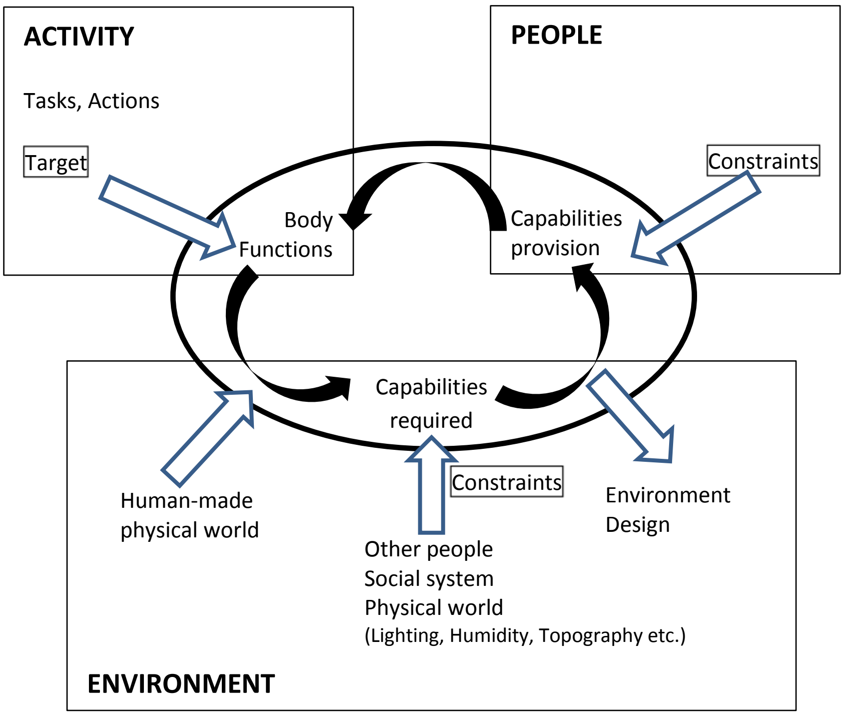


Figure 2-2: Activities-individual-environment structure.
Modified from Cepolina and Tyler (2004)

The Capability Model serves as the theory to discuss accessibility of the footway environment in this thesis. In the following sections, previous research will be reviewed based on the theoretical framework of the *Capability Model*. The review of *Provided Capabilities* (Section 2.2) includes sensory, physical and psychological characteristics of older people; the review of *Required Capabilities* (Section 2.3) includes pavement design, maintenance guides, lighting design and building codes. Despite the fact that the interaction between *Provided Capabilities* and *Required Capabilities* (approaching step-heights on the pavement), in which this thesis is interested, has little information in the literature, relevant research in walking in the built environment such as stepping performance as well as walking on stairs will be reviewed to illustrate the variables that could be considered (Section 2.4).

2.2 Provided Capabilities

The *Provided Capabilities* provided by pedestrians in the footway environment includes sensory, physical and psychological capabilities, such as obstacle detection ability and body functions, provided by pedestrians. This section will review the sensory, physical and psychological characteristics, and the most common physical problem happening to older people in the footway environment – falls.

2.2.1 Sensory, physical and psychological characteristics of older people

Previous research in the postural and gait characteristics along with sensory and physical abilities of older people, combined with the epidemiological studies on fear of falling, helps to explain the risks of falling in the elderly.

2.2.1.1 Sensory capability - vision

Balance control during walking consists of three components: sensory, motor and central processing systems, in which many subcomponents contribute to dynamic balance (Sturnieks et al., 2008). Any deficiency in any of these systems will lead to changes in movement strategies to maintain equilibrium and balance control, and result in high risks of falling. The visual system leads human locomotion by sensing environmental stimuli and then providing visual information for the cognitive process so that neurological responses can direct the biomechanical system accordingly, namely, what people see influences how and why they make a particular footstep later.

Campbell (2005) suggested that due to age-related changes in vision, people at age 60 need three times as much light as 20-year-olds need to navigate at home, which means that older people may have greater risk of falling while walking in a low-light environment and the perception of this heightened risk gives rise to an increase in the fear of falling. With age-related reductions in contrast sensitivity, stereoacuity and colour sensitivity, older people are vulnerable to the pedestrian environment due to their insufficient capability to sense the streetscape (Lord and Dayhew, 2001). As the abovementioned visual functions inevitably degenerate with age, walking on the pavement is becoming a dangerous outdoor activity for older pedestrians. Furthermore, along with other sensory and physical functions, the visual function degenerates with age-related diseases, such as cataracts, glaucoma, macular degeneration and diabetes, exacerbating the ageing visual function (Darowski, 2008).

2.2.1.2 Sensory capability - vestibular sensation and proprioception

In addition to vision, vestibular sensation and proprioception are thought to be another two important subcomponents in the sensory system with regards to the control of stability (Horak, 2006; Lord et al., 2007). Vestibular sensation tells people their spatial relationship towards the environment as well as providing a sensation of movement. Proprioception gives people the sensation of positions and movements of parts of the body (Darowski, 2008; Lord et al., 2007). For instance, in vestibular sensation, nociceptive input (the response to pain) from the foot signals the unevenness of the pavement so the according neurological and biomechanical response can respond and attempt to prevent a person from tripping. It is more noticeable when a person walks in the dark, because the vestibular and proprioception systems quickly compensate for the loss of visual information and hence enable the person to navigate through the darkness. Sensory information feedback is passed into the brain’s Central Nervous System, which has to integrate the information to figure out where the limbs are and then which movement or coping strategy to be adopted.

2.2.1.3 Physical capability

Studies on the postural stability of older people show that falling in older people is partly considered to be the consequence of degeneration in physical conditions, along with sensory and nervous systems. In order for a person not to fall over it is essential the centre of mass remains within the base of support (Horak, 2006). Horak (2006) indicated that the quality of the base of support and the control of the body's centre of mass are affected by 1) balance disorders and 2) diseases causing abnormal representation of the perception of postural stability and orientation in space, resulting in changes in gait cycles of older people, who are most likely to suffer from the disorders. The result is a gait style which exhibits as stepping rather than walking. This conservative pattern is characterised by a reduced velocity, wider step width, shorter stride length, and increased double support (when both feet are in contact with the floor) period (Kressig et al., 2004; Menz et al., 2003; Prince et al., 1997; Winter et al., 1990). These adaptations create a larger base of support for coping with disturbances to ensure people do not move their centre of mass beyond the base (Horak, 2006). In addition, older people also have a weak medial-lateral stepping control (Chapman and Hollands, 2010) with the tendency to initiate arm movements for maintaining their centre of mass and reaching for external supports (Maki and McIlroy, 2006). These coping strategies are, on the one hand, crucial to maintain the centre of mass within the boundary of the base of support and, on the other, supplementary to the ageing vestibular (Cohen et al., 1996; Sturnieks et al., 2008) and Central Nervous Systems (Horak, 2006).

Walking is a complex process, which requires fine timing of different body systems and functions, so that motion can be obtained. Traversing along a footway requires the body to be put off-balance – lifting one foot and projecting it forward, shifting the centre of mass forwards, placing the raised foot back onto the ground and then repeating the process with the other foot. To achieve this without falling requires physical and sensory capabilities and confidence that the regaining of balance will occur at the right moment before a fall occurs. The degenerating capabilities common in older age means that older person responds by protecting the stability of their centre of mass. This leads to the image of an older person's walking actions being characterised in comparison with a younger person's as being slower, having shorter steps, with the feet wide apart, more time with both feet on the ground, increased arm movements, including reaching for supporting objects – all in order to maintain the centre of mass within the bounds that falling will not take place.

2.2.2 Mechanism of falls on footway and environmental interventions

In Chapter 1, falls were recognised as one of the most common physical problems older people face and can cause various severe physiological, psychological and financial consequences. In the following sections, the definition, causes and psychological consequences of falls will be reviewed.

2.2.2.1 Definitions of a fall

The definition of a fall given by the Kellogg International Working Group on the Prevention of Falls in the Elderly as 'unintentionally coming to the ground or some lower level and other than as a consequence of sustaining a violent blow, loss of consciousness, sudden onset of paralysis as in stroke or an epileptic seizure' is regarded as the a frequently cited standard (Hauer et al., 2006; Lord et al., 2007). The Prevention of Falls Network Europe (ProFaNE) group define a fall as 'an unexpected event in which the participants come to rest on the ground, floor, or lower level' (Lamb et al., 2005). The World Health Organisation (WHO) defines falls as 'inadvertently coming to rest on the ground, floor or other lower level, excluding intentional change in position to rest in furniture, wall or other objects', but also indicates that an operational definition is left unspecified in many falls studies without an explicit designated standard (World Health Organization, 2007). The ProFaNE group (Hauer et al., 2006) systematically reviewed fall definitions in published articles and discovered 44 out of 90 reviewed papers did not provide falls definitions. Of those that did, some amended the Kellogg International Working Group's definition by including or excluding falls criteria for statistically significant results, others had self-defined criteria, and still others were not even referenced, hence there was no universal standard. The Prevention of Falls Network Europe and Outcomes Consensus Group (Lamb et al., 2005) suggests that when asking participants about their falls experience the operational definition of falls should be considered as ‘In the past month, have you had any fall including a slip or trip in which you lost your balance and landed on the floor or ground or lower level?’. The operational definition indicated that a fall could be induced by a trip, which, along with stumbling, is most commonly defined as ‘a sudden arrest of movement of a foot with continued motion of the body’ (Loo-Morrey and Jefferies, 2003; Manning, 1983). Although strategies for recovery from a trip were investigated (Pavol et al., 2001), the probability of tripping and the physiological and environmental contributions to respond to risks of tripping is yet to be fully investigated (Lord at el., 2007).

2.2.2.2 Falls in the footway environment

Causes of falls are divided into two groups, intrinsic factors and extrinsic factors (Darowski, 2008). Intrinsic factors are functions of a person’s capabilities, such as physical and cognitive functioning, medications, and anxiety. Extrinsic factors are things to do with the environment, such as changes in level of the pavement, lighting levels, and ambient sounds. Extrinsic factors such as trips and accidents outdoors were more likely to be reasons for falls than intrinsic factors such as dizziness and blackouts (Bath and Morgan, 1999).

Darowski (2008) indicated that most falls are the results of trips, slips and stumbles that we commonly experience while walking. For young people, stronger muscle strength and quicker reaction help prevent a stumble from converting into a fall but older people are more likely to turn a stumble into a fall. The ageing sensory, physical and psychological functions result in the increased number of stumbles; hence the occurrence of falls increases. As falls are related to trips and stumbles, it is valuable to review not only older people’s ability to sense as well as react to the footway environment containing commonly seen step-heights (which is described in Section 2.2.1) but also the outdoor environment that possibly induces trips and stumbles (Section 2.2.2.3 and Section 2.3). This thesis studies how the individual maintains as well as adjusts the balance mechanism while walking towards the obstacle on the footway as the performance of balance mechanism could give insights into the risk of falling for the individual.

2.2.2.3 Outdoor falls

Outdoor falls account for more than half of the falls in older people (Bath and Morgan, 1999; Bergland et al., 1998; Kelsey et al., 2010; Li et al., 2006; O'Loughlin et al., 1994), but little information is available on the investigation and intervention on environmental hazards (Kelsey et al., 2012). Nevitt and the colleagues (1991) indicated that activities such as walking and going up or down stairs, steps or kerbs were likely to cause fall-induced minor injuries and that these were also the two most common activities underway when a fall occurred. Li and colleagues (2006) also suggested that falls occurred most often during the activity of walking, accounting for more than 45% among people aged 65 and over, and walking was more likely to induce outdoor rather than indoor falls (Bergland et al., 1998; Kelsey et al., 2012). Pavement, kerb and street were found to be the places on which outdoor falls occurred most often (Kelsey et al., 2012) and the causes of outdoor falls were uneven surfaces (Li et al., 2006) and tripping on something (Bath and Morgan, 1999; Li et al., 2006). Considering the comparatively smaller amount of time older people spend outdoors than indoors, the possibility of outdoor falls was remarkably higher than that of indoor falls (Li et al., 2006).

2.2.2.4 Fear of falling

The fear of falling caused by the risks of falling and fall-induced injuries can also deteriorate the physical and psychological functions of older people. Fear of falling is particularly prevalent among women with higher age, and those who have had at least one fall (Arfken et al., 1994; Austin et al., 2007; Howland et al., 1998; Scheffer et al., 2008; Zijlstra et al., 2007). Physical constraints such as poor perceived general health (Zijlstra et al., 2007), depression (Austin et al., 2007) and functional decline (Brouwer et al., 2004) are also important factors. Furthermore, fear of falling may trigger a vicious circle of exacerbating the physical frailty and increasing the possibility of recurrent falls (Brouwer et al., 2004; Scheffer et al., 2008; Yardley and Smith, 2002). The fear-related avoidance of activities may decrease social contacts and support, and, as a result, cause depression and deteriorate quality of life (Howland et al., 1998; Scheffer et al., 2008).

Fear of falling might often be the result of a ‘near-miss’ or falls experience. However, many of those who have a fear of falling have not had any falls (Darowski, 2008; Howland et al., 1998). Adverse consequences of the falls incidents of their friends or relatives could also induce fear of falling and further deteriorate the quality of life (Howland et al., 1998).

2.3 Required Capabilities

The *Required Capabilities* are defined as the capabilities required by the footway environment to achieve a given task. The physical constraints imposed by pavement design, footway maintenance and lighting level determine the capabilities the individual might need to complete the task.

2.3.1 Pavement design and maintenance guidelines

Although previous research has shown the importance of the quality of the pavement to older pedestrians (Burton and Mitchell, 2006; Help the Aged, 2007b; Inclusive Design for Getting Outdoors, 2007), to what extent a given pavement can be reckoned to be a well-maintained pavement is still unclear. The Department for Transport (2005) published a guide on best practice on access for pedestrians, which takes into account the needs of people with reduced mobility, such as wheelchair users and people with walking aids. These guidelines indicate best practice geometry of pavements such as width and gradient, however, the sensory and physical capabilities of older people are not addressed in this guidance. Given that many older people have more than one type of cognitive, sensory or physical impairments, the capability required by the pedestrian environment might be beyond an older person’s capabilities and therefore navigating around the built environment becomes risky.

One principal design characteristic of pavements which has been shown to induce falls is a change in level. Changes in level along a footway occur mainly for two reasons: 1) a step which has been designed into the built environment or 2) an unplanned subsidence or rising of a section of the pavement. Various changes in level can cause different degrees of danger and risk of falling to pedestrians. The Inclusive Mobility Guide (Department for Transport, 2005) suggests a riser height for steps and stairs of between 100 mm and 170 mm with a commonly acceptable height of 150 mm, and a standard kerb height ranging between 125 mm and 140 mm. The UK Pavement Management System (UKPMS) user manual indicates the threshold of 30 mm between moderate and severe local settlement/subsidence on footways of all kinds of paving (Pickett and Gallagher, 2010), and Westminster Council sets out in the Street Standard (Westminster City Council, 2011) that defects such as cracks and holes of 20 mm on standard pavements or 30 mm on cobbled pavements should be seen as potential safety hazards. In contrast Bird and colleagues (2006) suggest a maintenance threshold of 13 mm and a safety defects threshold of 20 mm based on the records of a total of 1,307 third party claims following footway accidents against three local councils in the UK between 1998 and 2002. Murray (1967) found that half of the participants had their foot caught by a defect of around 15 mm and all of them tripped by a defect of 40 mm. However, the probability of a trip decreased for changes in level greater than 40 mm due to higher visibility of the defect.

For the sake of the discussion, a single change in level, such as kerbs, will be named as a *step-height* throughout the rest of this thesis.

2.3.2 Building regulation

Despite the fact that the nature of stairs is different from that of step-heights and the perception is also different, the design guidance for stairs provided by the Building Regulation 2010 could still give insight into the design of steps. The Regulation (Department for Communities and Local Government, 2013) suggests the rise (the vertical gap between two consecutive steps) ranging between 150 mm and 170 mm, and the going (the horizontal gap between two consecutive steps) ranging between

250 mm and 400 mm for general access stairs but the rise and going of each step should be kept consistent throughout a flight of stairs .

2.3.3 Street lighting

The Manual for Streets (Department for Transport, 2007) suggests that street lighting for better-designed streets should be able to reduce risks at night time, discourage crime against properties and provide security. The lighting level should be designed in line with the guidance in BS 5489-1 (British Standards Institution, 2012) with the criteria in BS EN 13201 (British Standards Institution, 2003). The Manual for Streets, however, only suggests lighting source as a possible indicator of different streets, such as whiter lighting for residential streets and sodium lighting for traffic routes.

The European Standard EN 13201-2:2003 provides more detailed criteria for street lighting than the Manual for Streets (Department for Transport, 2007) by indicating the S classes for pedestrians on footways. The S series consists of six lighting classes ranging between 2 lux and 15 lux. The British Standards BS 5489-1:2013 (British Standards Institution, 2012) also suggests the S series lighting classes in subsidiary roads for pedestrians to navigate in the pedestrian areas, be informed of hazards and other pedestrians, and for reducing crime against pedestrians and properties. These purposes were also identified as the visual tasks for pedestrians.

2.3.4 Lighting for pedestrians

Raynham (2004) did a review on the fundamentals of road lighting for drivers and pedestrians and identified three key tasks performed by pedestrians: obstacle detection, orientation and facial recognition. Each task is a human factor in road lighting and requires different amounts of lights (Raynham, 2007, 2006). The purpose for obstacle detection is for pedestrians to make safe movement and being able to detect the unevenness and small obstacles on the pavement. As orientation was associated with wayfinding and facial recognition is related to the general feeling of safety (Fotios et al., 2013), obstacle detection is the task mainly associated with walking behaviour with regard to the quality of the pavement.

Given that tasks performed by pedestrians are considered as a human factor in road lighting, Fotios and colleagues (2013) suggest there is the involvement of the individual's sensory capability in the footway environment. It also means that the lighting level should meet pedestrians' needs to navigate in the ambient area. When these results are brought into the *Capability Model*, the lighting level becomes one of the *Required Capabilities* whereas pedestrians' sensory and physical responses become the *Provided Capabilities*. It would be worth investigating the coping strategy used by the individual to plan gait adjustment at different lighting levels so that the association between lighting level and the perception of visual information as well as the foot adjustments could be further understood. In addition, previous research studies in lighting were carried out in a static environment (Fotios and Cheal, 2012, 2009) in which some tasks as well as elements in the real footway environment, such as walking and paving conditions, were not taken into consideration.

2.3.5 Lighting for older people

Based on the European and British Standards, several researchers conducted studies on the individual's capability of detection under different street lightings. Fujiyama and colleagues (2007) simulated a footway in a controlled laboratory to investigate the perception of hazards in the street. In the pilot study, a 74-year-old male was recruited and requested to walk along five walkways of level surface, horizontal gaps, 1.3m height obstacles and two types of step alignments at four lighting levels of 241, 27, 4.5 and 0.85 lux. This study suggests a visible as well as justifiable methodology to understand older people's perception of physical hazards based on the eye tracking technology other than the widely used self-report method. One of the results showed that in low lighting environments, the participant fixated his gaze more on the hazard objects, such as horizontal gaps, steps and obstacles, than on the orientation objects. Identifying an object in lower lighting environments took more time than in brighter lighting environments.

Another result revealed the effects of the direction of steps on visual perception, which have been discussed in studies in walking on stairs (see Section 2.4.2) but rarely in the footway environment. The total fixation duration increased as the height of ascending step-height increased, but decreased as the descending step-heights became more considerable. The result further implied that the visually ambiguous hazards did not attract visual attention in spite of the associated actual danger. Therefore the defects of the pavement design and the associated actual danger were not always being visually perceived (Fujiyama et al., 2007).

Previous research in walking on stairs might be able to shed some light on the visual perception of visually ambiguous hazards (Den et al., 2011; Miyasike-daSilva, 2011; Miyasike-daSilva et al., 2011; Zietz and Hollands, 2009). Ascending stairs attracted more visual attention than descending stairs due to higher visibility attached to ascending stairs (Miyasike-daSilva and McIlroy, 2012).

The effects of the visibility of step-heights on older people’s gait pattern, however, were unknown in Fujiyama and the colleagues' study (2007). In addition, the finding from studies in walking on stairs might need further validation in the footway environment. But the initial results in the Fujiyama and colleagues' study (2007) suggest further investigations would be needed to understand the visual perception of step-heights on the pavement at different lighting levels and also the gait pattern associated with the gaze behaviour in the elderly.

2.3.6 Movement under emergency lighting

Despite the fact the nature of fire evacuation is different from that of walking on the pavement, the minimum emergency lighting could be seen from the perspective as a suggestion for the absolute minimum lighting required for navigating in the built environment. Boyce (1985) set up five evenly or unevenly lit illuminance conditions with 60 participants, 12 for each emergency lighting condition. The results showed that older participants tended to walk to escape routes more slowly than young participants. A mean illuminance of 0.2 lux was sufficient enough for evacuation and the evacuation at a mean illuminance of 1 lux had very little difference from the performance at normal room lighting level.

The results of the study reveal that absolute minimum illumance levels of 0.2 lux and 1 lux were regarded to be sufficient to help individuals move to escape routes. However, in the footway environment, which has more elements and fewer survival-driven decisions, a higher illuminance level might be required to detect obstacles as well as hazards on the pavement. Therefore studies in the lighting level for the footway environment might look for a illuminance level higher than 1 lux.

2.3.7 Environmental interventions against risks of falling

Environmental interventions mostly deal with interior risk factors, hence associations between risk factors and outdoor falls have not been correctly addressed, making the magnitude of outdoor falls uncertain (Kelsey et al., 2012). Lord and colleagues (2007) noted that the interaction between the outdoor environment and older people's physical capabilities appeared to be more important than domestic hazards in falls. The WHO Safe Community Program implemented in Motala municipality in Sweden between 1983 and 1999 conducted community interventions against injuries, including falls injuries, in older people (Lindqvist et al., 2001). Environmental interventions such as road maintenances, pavement reconfigurations and lighting improvements were found to have contributed to the decrease in fall injuries but the magnitude of the intervention as well as published studies concerning intervention in outdoor environment were not fully understood (Li et al., 2006). Gillespie and colleagues (2003) conducted a comprehensive review on published falls interventions from randomised controlled trials in older people, and among the studies reviewed, although safety of the home environment was addressed, no attention was given to the outdoor environment. To date, there is little literature on environmental interventions and standardised methods, let alone understanding the interaction between the footway environment and older pedestrians; therefore there is a need for a new approach to detect the effects of footway environment on the *Provided Capabilities* in older people by measuring the sensory as well as physical responses to demonstrate personal capabilities in relation to the footway environment.

2.4 Walking in the built environment

Walking in the built environment is one of the person-environment interactions the individual performs on a daily basis. The individual walks along the footway in order to carry out some forms of *Activity*. While carrying out the *Activity*, the *Provided Capabilities* and *Required Capabilities* interact and the sensory as well as physical responses decide if the *Activity* is achievable. There has been a wide range of discussion in the *Provided Capabilities* (sensory and physical capabilities) during obstacle clearance, stepping movement and walking on stairs in the built environment. The review might provide insights into understanding how *Provided Capabilities* and *Required Capabilities* would interact with one another in the built environment.

2.4.1 Sensory and physical capabilities of responding to obstacles on walkways

When negotiating with an obstacle or a step-height, visual information in the ambient environment is critical in the control of locomotion and the estimation of the position of the obstacle, and then a minimum toe clearance is adapted to clear the obstacle or the step-height. Older participants aged 60 and over tended to have earlier gaze into the direction of the obstacle or longer gaze on the obstacle itself compared with middle-aged and young participants (Chandra et al., 2011). Harley and colleagues (2009) indicated that participants aged between 70 and 79 had increased leading toe clearance but reduced trailing toe clearance as well as reduced velocity during verbal fluency dual-tasking trials, which was thought to be a compromised safety margin caused by increased cognitive demands, leading to a posture-protective strategy. Given the complexity of the relationship between vision, postural and gait control, and ageing, when any of the defects is found interrupting balance control, falls happen as a result of the incapability to gain or regain the body's balance.

In order to compensate for the age-related loss of sensory and physical functionality, older people develop conservative strategies to navigate in the built environment. Researchers studying the relationship between eye movements and gait patterns discovered that people looked at targets two steps ahead when walking (Patla and Vickers, 2003), and older people were more likely to fixate on the immediate target sooner and more often, and then saccade away to the next target earlier than younger people (Chapman and Hollands, 2006, 2007). These results suggested that older people tended to prioritise planning coping strategies over current stepping (Chapman and Hollands, 2007) and requested additional attention to deal with a more complex environment (Lamoth et al., 2011). These studies indicate that older people may develop a conservative navigation strategy in order to decrease the risk of falling as well as increase their confidence in walking outdoors.

2.4.2 Strategies used for walking up and down stairs

Previous research in stepping performance in relationship to gaze behaviour mainly studied the performance of stepping on level or raised stepping targets. The footway environment includes not only ascending but also descending step-heights and therefore the gaze and gait behaviours around descending step-heights should be further studied. To the best of our knowledge, there is little research in the combination of gaze and gait behaviours during either step-descent tasks or while the individual is approaching the obstacle, but, having said that, research in walking on stairs might be able to provide some reference to the sensory and physical capabilities of walking on the pavement with step-heights.

Zietz and Hollands (2009) studied the gaze behaviour of ten younger and ten older participants walking up or down a flight of stairs of 12 steps. The result in the difference in the gaze behaviour between stair-ascent and stair-descent tasks showed that during stair-descent, before heel contact happened, participants transferred fixations from the level surface onto the stair later and then also gazed away from it later as opposed to stair-ascent. It suggested that visual information was more demanded for stepping movements during stair-descent. This gaze characteristic may supplement the finding in research in dynamic posture stability revealing stair-descent caused more disturbances to gait stability and possibly increased higher risk of falling (Bosse et al., 2012; Mian et al., 2007; Zietz et al., 2011).

Zietz and Hollands' study (2009) also showed age-related differences in the correlation between gaze and gait behaviours. Older participants transferred gaze fixation onto the stairs sooner and fixated on the stairs longer than younger participants, indicating that older participants required additional fixation time for additional visual information in order to make stepping movements. This gaze characteristic may be the gaze coping strategy for older participants to make accurate stepping performance. The age-related difference in gaze behaviour also showed that there were age-related changes in visuomotor control.

Miyasike-daSilva and colleagues (2011) conducted research in the gaze behaviour in relation to the location of fixations while walking on stairs. In this study, a 2.23 m landing pathway was attached to both top and bottom steps and therefore the gaze behaviour of 11 young participants on the transition phase (from the level surface to the stair) could be investigated.

Miyasike-daSilva and colleagues' (2011) study revealed that gaze fixation fell 2-4 steps ahead of participants’ location during stair-ascent and 4 steps ahead during step descent. The gaze behaviour in the transition steps area did not demonstrate significant behaviour and one of the reasons was suggested to be a lack of task complexity and task specificity. However, Miyasike-daSilva and McIlroy's (2012) study showed that the reaction time of locomotion in the transition phase increased due to additional executive demands of stepping adjustments. Therefore gaze and gait behaviours would be worth studying with environment complexity. Trial effect was not found in this study as participants might have adopted their real-life stairs walking experience and also there was not any irregular step designed into the experiment.

The methodology of analysing gaze behaviour during transition steps used by Miyasike-daSilva and McIlroy (2012) could serve as a reference for the area of interests during obstacle clearance or passing step-heights. In addition, the increased reaction time found in previous research would be worth being investigated in gait analysis in this thesis in order to further understand further how the gait adjustment was made by various gait variables. One single step-height of random height, either descending or ascending, designed in the experiment of this thesis would create a certain level of irregularity and a longer walkway as well as a more complex footway environment, including different lighting levels, might be able to explore the gaze behaviour relating to step-height while the individual is approaching the obstacle or hazard on the footway.

2.4.3 Vision

The characteristics of vision used during walking tasks are reviewed in the following sections. The review begins with the age-related visual performance in obstacle detection (Section 2.4.3.1), followed by the locations where the gaze fixates (Section 2.4.3.2), the two indicators of gaze behaviour – fixation and saccade (Section 2.4.3.3) and then the effects of lighting level on the obstacle detection (Section 2.4.3.4).

2.4.3.1 Ageing and vision in obstacle detection

Fotios and Cheal (2009) investigated the effects of light source, illuminance and age on obstacle detection in peripheral vision in the static low light environment. Three lighting levels of 0.2, 2.0 and 20 lux, and eight raised heights of 0.40, 0.50, 0.63, 0.79, 1.00, 1.26, 1.58, 2.00, 2.51, 3.16, 3.98, 5.01, 6.31 and 7.94 cm were set up at six different locations for 11 young (under 45 years) and ten old (over 60 years) participants. Participants were requested to self-report once any obstacle was detected. The results suggested that the ability of obstacle detection was affected by illuminance level and the detectable height was lower at 20 lux than at 0.2 lux. The young age group was able to detect a lower obstacle at 0.2 lux better than the older age group, but at 20 lux the two age groups did not show a difference in obstacle detection (Fotios and Cheal, 2009), suggesting that the difference at 0.2 lux may be due to age-related degeneration of vision in older participants.

Fotios and Cheal's (2009) study revealed the effects of lighting level on obstacle detection regarding obstacle height and ageing. Even though the study was carried out in a static environment with monocular vision, the findings might suggest further studies in the visual perception in the footway environment.

2.4.3.2 Locations of gaze

Davoudian and Raynham's (2012) study took the real environment into consideration. Eight male and seven females aged between 20 and 60 years walked along three different types of routes with an eye tracker: a residential street with a limited amount of traffic, a purely residential street and a collector road in the company of a researcher. The first two routes were conducted with the task of navigating to a designated point whereas in the last route participants were purely led by the researcher. The overall result suggested that participants looked down at the pavement between 40% and 50% of the overall time. In a route with more obstacles, the observed time spent on the pavement was longer. Davoudian and Raynham (2012) suggested that the amount of time spent on the pavement may be the time left after participants scanned the environment and therefore the more complex or insecure the environment, the less the amount of time spent on the pavement (and thus more on the surroundings). The result also suggested that in the real environment participants tended to look farther away than two steps suggested in the previous study based on walking on treadmills (Patla and Vickers, 2003).

According to Davoudian and Raynham's (2012) study, the investigation of visual behaviour in the real footway environment was necessary as people actually spent considerable time looking down on the pavement but there was little information about what they might look at. In addition, given that treadmill experiments considered few elements in the footway environment but the real environment consisted of too many confounding factors, it would be worth carrying out a study in a controlled environment with limited footway elements so that the gaze behaviour could be further understood.

2.4.3.3 Fixation and saccade

Previous research (Fotios and Cheal, 2009; Marigold and Patla, 2008, 2007; Zettel et al., 2005) found that gaze fixations (as foveal visual information) were not required during tasks like unpredictable postural disturbance and obstacle detection; however, the visual behaviour of fixations actually reflected the demand from the Central Nervous System for the optimal amount of information in order to make gait adjustments, especially walking across complex ground terrain (Marigold and Patla, 2007).

Hollands and colleagues' (1995) study in the association between gaze behaviour and stepping also revealed that gaze fixations were possibly being used to control as well as fine-tune the footfall on the targets.

In this thesis, therefore, visual fixation serves as an indicator of the visual attention required by the Central Nervous System. The gaze behaviour of fixations represents the visual information the individual demands to detect the step-height.

2.4.3.4 Lighting in a static environment

Fotios and Cheal (2012) conducted a study in obstacle detection in a controlled and static experimental setting to understand the appropriate illuminance in residential roads. The result showed 5.7 lux was a threshold of appropriate road surface illuminance, after which the detection performance gradually stabilised. This study defined the dimension of a critical obstacle of 25 mm in height with 6 m ahead down the footway at the lighting level of 1.8 lux. Four young participants with equal number of both sexes were recruited and a repeated measures design consisted of five illuminance levels, four obstacle locations and eight obstacle heights was conducted. Participants were requested to self-report once they noticed any obstacle on the surface.

Fotios and Cheal's (2012) study, despite the fact that the experiment was conducted in a static environment, provided insights into an appropriate illuminance for street lighting for raised obstacles at pedestrians’ conscious level.

2.4.4 Gait and stepping movement

Gait behaviour in relation to walking or stepping is reviewed in the following sections. The review begins with the age-relation characteristics in gait (Section 2.4.4.1), followed by the application of gait variability (Section 2.4.4.2), gait performance during stepping movement (Section 2.4.4.3) and the trial effect (or learning behaviour) used to deal with the environment (Section 2.4.4.4).

2.4.4.1 Ageing and gait patterns

Chapman and Hollands (2006) investigated the age-related difference in the gaze behaviour associated with changes in stepping performance and found that older people needed more time to plan precise foot placements yet the accuracy of stepping performance was lower as opposed to young people. Eight young participants and eight older participants (half being at low-risk of falling and half at high risk of falling) were requested to walk along a 9 m walkway and then step accurately in two target locations. All of the older participants transferred gaze on the targets earlier and then made longer fixations than younger participants. Older participants at high risk of falling transferred gaze away from the first target earlier and then made longer fixation on the second target than the other participants. With regard to the stepping variability, older participants at high risk of falling demonstrated higher medio-lateral stepping variability.

Chapman and Hollands' (2006) study suggested that the earlier gaze attention to the first target was the result of longer ‘looking down’ gaze of older participants than younger participants and it might be because of degenerated vision, cognitive and/or biomechanical functions, older participants needed additional time to process visual information of the targets. For older participants at high risk of falling, the Central Nervous System might also demand additional time to plan the following actions to respond the upcoming target and therefore gaze was redirected to the next target earlier than younger participants. The earlier gaze transfer was associated with less accurate stepping movements and it might be the prioritisation of gaze transfer over footstep accuracy that contributed to trips and falls, reflecting a deficit in cognitive attention to hazards.

Chapman and Hollands (2007) carried out a follow-up study in the correlation between gaze and stepping performance in both young and older people in the cluttered walking environment. Six young participants and six each for the older participants at low risk as well as high risk of falling took part in three walking tasks: single stepping target, two stepping targets and two stepping targets with a raised obstacle in between.

The finding of Chapman and Hollands' (2007) study revealed that in the walking task with a single stepping target there was no significant difference in gaze transfer relating stepping movement between participant groups. However, while negotiating two stepping targets or two stepping targets with an obstacle in between, older participants at high risk of falling transferred their gaze away from the first target earlier than the other participant groups and the success rate of stepping performance dropped as well. It suggested that the degenerated cognition, physical responses and increased anxiety over upcoming stepping targets/obstacle might contribute to older participants' early gaze transfer and also affect their ability to pre plan the stepping movement. The association between this early gaze transfer and decreased success rate of stepping performance suggested that the gaze coping strategy implemented by older participants might actually increase the possibility of falls.

Chapman and Hollands' (2010) later study on used light emitting diodes (LEDs) to create unexpected stepping targets on the walkway to study the correlation between gaze and stepping movement for ten young was well as older participants. The findings revealed that older participants at high risk of falling transferred their visual attention from central LEDs to target LEDs later than the other participant groups. But as the vision functions for each participant group had no significant difference, the result suggested it might be the age-related decline in visuomotor control contributing to the gaze characteristic. However, in terms of the visual fixations, older participants at high risk of falling demonstrated earlier gaze fixation transfer than the other participant groups (that is to say, they started the transfer earlier but the process is longer) but in the meantime they made more medio-lateral stepping errors. This study suggested that older participants at high risk of falling might be suffering from the degenerated Central Nervous System, visual, cognitive and physical functions. Therefore additional time was required to initiate the visual transfer as well as fixation on the stepping targets in order to make rapid medio-lateral stepping movements.

Young and Hollands (2010) then investigated the intervention in the deficit gaze as well as stepping performance in older participants. Sixteen older participants were requested to take part in three walking tasks: single stepping target, two stepping targets, and two stepping targets with a raised obstacle in between. All participants carried out each walking task and then half of the participants, as the intervention group, were requested to maintain gaze on the stepping targets until heel contact. The results showed that reduction in mean stepping error, stepping variability and task failure were all associated with the intervention. The delayed gaze transfer might contribute to improved online corrections in stepping movement and as a consequence, a delay in shifting attentional resources might help improve the accuracy of stepping performance.

2.4.4.2 Gait variability

Hausdorff and colleagues (2001) investigated the factors contributing to gait instability and revealed that the causes for gait instability in older people were multifactorial (Figure 2-3). Both physiological and neuropsychological factors might be correlated to gait instability, and age-related changes could further affect the physiological functions as well. Gait variability of the stride time of this study was used to understand the fluctuation magnitude of gait instability. The result showed that the stride time variability had a strong negative association with functional status, such as activities of daily living, physical function, depression symptoms and body mass index, etc. Hausdorff's (2005) systematic review summarised that gait variability, including gait speed, step length and stride time, was associated with clinical syndromes relating to falling and age-related diseases and therefore gait variability might be a clinical indicator of mobility, risk of falling and efficiency of therapeutic interventions.

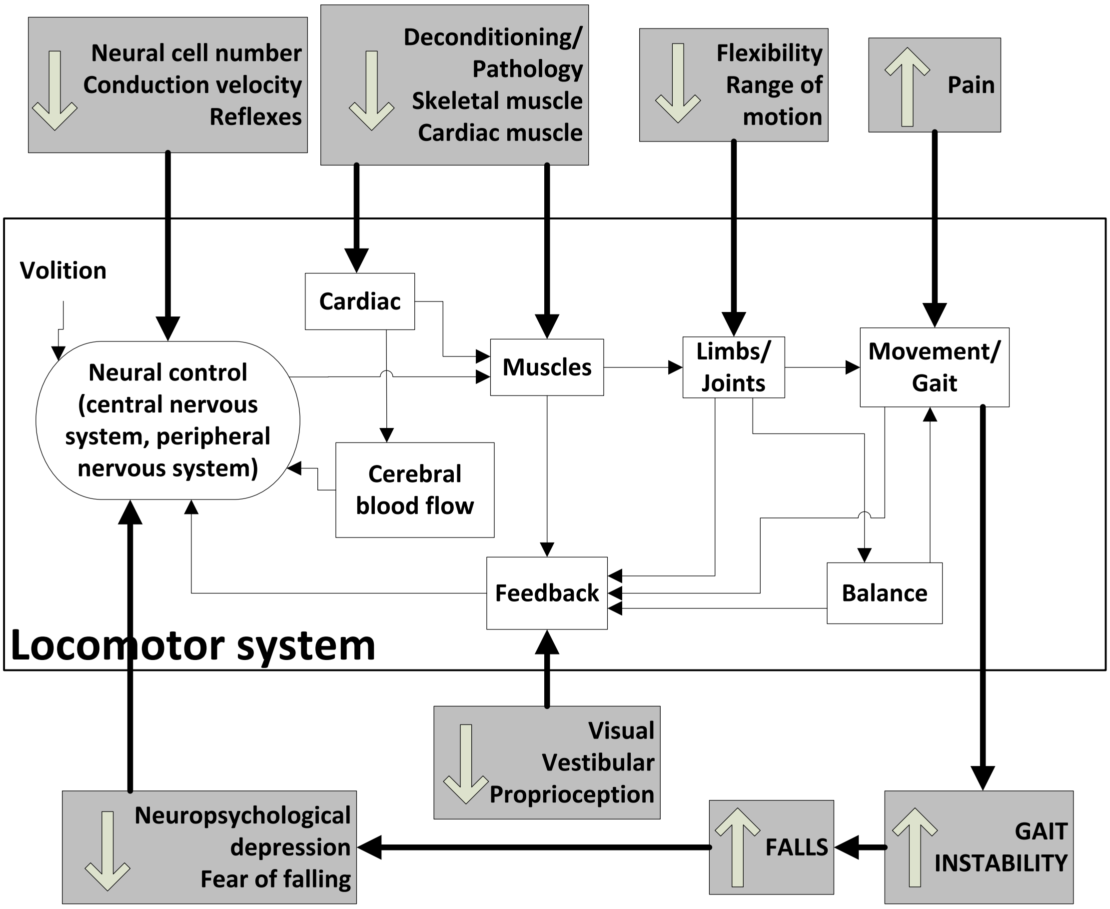


Figure 2-3: Simplified diagram of the locomotor system.
Physiological and neuropsychological factors in shaded boxed indicate age-related changes.
Modified from Hausdorff, 2005; Hausdorff et al., (2001)

2.4.4.3 Stepping behaviour

The study in stepping behaviour might be able to provide some insight into how the input of visual information was transformed into physical response. Patla and Vickers (2003) conducted a study in stepping performance to understand the relationship between visual fixation and stepping patterns. Seven participants were requested to walk along two types of 10-m walkway with 17 footprints each (as stepping targets): regular intervals of average step length and width, and irregular intervals. The results suggested that participants fixated on the upcoming stepping target two steps ahead, about 800 – 1,000 ms, which was thought to be sufficient to perceive visual information and then calculate the gait adjustment. Land (2006) repeated the protocol on a pavement with cracks on which participants were requested not to step on the cracks. The result suggested that participants looked at the crack 1.91 steps ahead with 1,110 ms, which was similar to Patla and Vickers's (2003) conclusion.

Patla and Vickers (2003) hypothesised that due to a lack of observable association between the gait adjustment to the upcoming step and the following steps, the nervous system might adjust dynamic balance step-by-step and the visual behaviour of targets fixations might be activated only when the balance is being disturbed.

2.4.4.4 Trial effect

Patla and Vickers (2003) found no trial effect across walking trials in their research, suggesting that participants did not make use of a mental map as the footway conditions were not consistent, relying on memory might cause mistakes. However, Zettel and the colleagues' (2005) study in the association between unpredictable postural disturbance and gaze redirection revealed that participants demonstrated the ability to remember the spatial information about the targets and obstacles. The Central Nervous System might utilise this mental map to direct vision as well as cognitive attention to other demands for balance mechanism.

2.4.5 Gaze and gait coordination

A comprehensive study in the correlation between eye and foot movement was conducted by Hollands and colleagues (2004). They investigated the temporal and kinematic correlation between eye, head, upper body and feet during a coordinated movement in the posture. The kinematic characteristics of all movement amplitudes of five young participants were studied. The results showed that the whole body movement was initiated by eyes, followed by head, upper body and finally down to feet, which showed the influence of vision on the body locomotion. In addition, this research also revealed that the correlation between eye and foot movement was statistically greater than the correlation between other body parts and feet movement. The significant correlation was represented by the latencies as well as amplitudes profile of movement between eyes and feet. The eye and feet systems were more coordinated than any other paired systems during whole-body movement in this study. The input (visual information) and output (gait adjustment) were closely collaborating with each other.

The finding of significant coordination between eye and feet systems further implied the information process from visual perception to feet movement. Therefore the approach in this thesis is to take eye and foot behaviours into consideration in a dynamic environment. As opposed to Hollands and colleagues' (2004) study, this thesis is interested in the gait movement in the footway environment instead of stepping or posture performances so the gait data, rather than kinematic data, were collected.

Patla and Vickers (1997) studied gaze behaviour during walking and how vision was used to affect walking. Eight participants were requested to walk along a walkway with an obstacle of 1 cm, 15 cm or 30 cm in height located randomly between 4 to 6 m ahead on the walkway. Fifteen trials were performed with five trials for each height. Gaze data were collected through an eye tracker with a sampling frequency of 30 Hz. Gait pattern was represented by the number of footsteps in relation to the occurrence of gaze behaviour.

The result of Patla and Vickers's (1997) study was ground breaking in many ways. Firstly, it suggested that the fixation on the obstacle as well as the 4-6 m area, where the obstacle was randomly located, was used as a feedforward mode, meaning that participants used the visual environmental information to control the gait movement. Secondly, the travel fixation, the gaze stably fixated ahead of the participant along with the locomotion, was used to control the walking speed, or the on-line control mode defined by Patla and Vickers (1997). Thirdly, it also revealed that the environmental information was sampled rather than fixated continuously as the perception of the environment was only one of the functions vision performed. The use of the eye tracker also helped complement the early studies in vision and validated the eye tracking technology in gaze and gait studies (Patla, 1997; Patla et al., 1996). Patla's (1998) follow-up study further complemented the critical roles of visual fixations on targets on the walkway.

With regard to the association between visual fixation and gait performance, Patla (1997) suggested that higher fixation frequency and longer fixation duration associated with the small and low contrast obstacles, indicating that the subtle obstacles required increased time for detection. For the higher obstacles, participants made more fixations due in part to an increased demand in making their precise footsteps in order to negotiate the obstacle which might be too high to overcome. Therefore the higher obstacles were also seen as more dangerous as there was an increased need to adjust participants' footsteps in order to overcome the obstacles.

2.5 Discussion and conclusion

In this chapter, we reviewed previous research in the individual's sensory and physical capabilities of walking, especially for older people, the current footway design manuals, and the coping/compensation strategy used by older people to navigate in the footway environment.

To the best of our knowledge, the gait and posture behaviour studies so far were mainly task-based (the accuracy or success rate of walking or stepping tasks) and/or kinematic-based in controlled gait laboratories. However, these previous studies were not fully representative of normal walking in the footway environment and the results might not be fully applicable to footway design. It would be worth understanding the foot movement from a different perspective, such as temporal gait analysis of double support time, how the gait is being adjusted along the walkway, and whether walking on the pavement would demonstrate different gaze behaviour from stepping performance.

Previous studies in eyes and foot movements showed statistically significant coordination as well as correlation between gaze and gait behaviours and also revealed how perceived visual information could affect the gait pattern in a feedforward way. The visual information of fixation reflects not only the demand for visual information from the Central Nervous System but also implies gait instability caused by either foreseeable or present disturbances. A study in walking in a dynamic experimental set up should be carried out to test previous assumptions and conclusions found in static experimental set-ups.

The experiment designs in previous research validated the instrumentation of the eye tracker in postural as well as stepping behaviour. Gaze fixation on the target was found to be registered two steps ahead of the individual, which gives us a reference of the length of the walkway to study the gaze behaviour. Gaze studies that considered detailed negotiation around obstacles did not include a length of walkway which would be needed to study gait patterns. Therefore as in this thesis, where the combination of gaze and gait will be investigated, it could be necessary to ensure that a walkaway length sufficient to allow both gaze and gait characteristics to be studied. A longer walkaway was therefore designed in this thesis to understand the gait behaviour in the footway environment.

Descending step-heights should also be brought into consideration in order to simulate the real footway environment. The gait behaviour of step-descent was investigated in studies in walking up and down stairs. However, the gait studies had little discussion on gait behaviour on the pavement where a single descending or ascending step-height is commonly designed in.

Previous studies showed contradicting findings in the trial effect (or learning behaviour). The use of memory (or mental map) might cause errors in footstep judgement but on the contrary the Central Nervous System might utilise the memory to direct the vision and attention for other demand of gait stability. As previous studies findings were opposing each other, in this thesis it would be worth investigating the trial effect on the coordination between gaze and gait behaviours in the footway environment consisting of different environmental factors.

2.6 Research questions

Studies in the individual’s sensory and physical capabilities have showed that older people do experience degenerated physical function which might make them feel aware of the footway environment. However, footway design guidelines do not have strong scientific support into the response of older pedestrians to the footway environment. Research in street lighting was mainly conducted in a static environment with participants detecting objects at different lighting levels, which could not be representative of real walking behaviour in the footway environment. However, the research of lighting level conducted in the real environment might have contained too many confounding factors such as sound and the intimidation of other pedestrians, which might have affected the gaze behaviour. Studies in the interaction between older people and the footway environment mainly focused on the behaviour in the transition and/or target areas or the performance of recovering from disturbances.

To the best of our knowledge, the planning as well as coping strategy of gaze or gait behaviours demonstrated while the individual is approaching an obstacle or a hazard has rarely been discussed, and relevant studies were mostly conducted either in a static environment or with static tasks, or both. As it is of great importance to understand how older people adjust their footsteps with visual information provided when walking along the footway, dynamic walking tasks in a dynamic footway environment should be simulated in order to understand the on-line visual perception as well as gait adjustment. This thesis therefore centres on the following questions:

Three questions pertain to the link between capabilities and the environment. These are:

- Q1) What is the association between the sensory capability (gaze) and the environmental factors (step-heights and lighting levels) in the footway environment?
- Q2) What is the association between the physical capability (gait) and the environmental factors (step-heights and lighting levels) in the footway environment?
- Q3) What is the interaction between the individual's sensory capability (gaze) and physical capability (gait) in the footway environment?

For each of the research questions (Q1 - Q3), the effect of age, sex and wearing glasses will be tested.

A secondary research question relates to whether there is a trial effect (learning behaviour) during the experiments, which would make the individual more familiar with a specific footway configuration. It was attempted to limit this effect by randomisation of trials, however, the research question still needs to be investigated:

Q4) How does the individual make use of the familiarity of the footway environment (trial effect) to make sensory (gaze) and physical (gait) responses?

The final research question looks into what impact this research has in helping to inform guidelines which would enable older people to negotiate the upcoming step-height:

Q5) Is there an optimum configuration of step-heights and lighting levels which shows a clear benefit to older people (i.e. reduce the *Provided Capabilities* of the individuals)?

Chapter 3: Research methods

Chapter 2 showed that the capability model can be used to explain the interaction between an individual and the footway environment but for further understanding of the capability provided by the individual and the capability required by the footway environment, it would be necessary to have a more comprehensive picture of the individual's approach to step-heights on the pavement. This chapter explains the methodologies and methods used to measure these *Provided Capabilities* and *Required Capabilities*.

This chapter is divided into two parts: the introduction to and development of methodology (Section 3.1 to Section 3.5) and the methods devised to measure the parameters of both *Capabilities* (Section 3.6 to Section 3.11). Section 3.1 explains the development of the parameters of an observed walking distance – the preparation phase (Section 3.1.1), *Required Capabilities* (Section 3.1.2), *Provided Capabilities* (Section 3.1.3) and interested age groups (Section 3.1.4). Section 3.2 further elaborates the performance measurement of both *Capabilities* in terms of the individual's sensory response (gaze behaviour) (Section 3.2.1), physical response (gait pattern) (Section 3.2.2) and the change in gait pattern in relation to the first visual fixation (Section 3.2.3). The capability of the measurement elaborated in Section 3.2 is then explained in Section 3.3 with regard to the measurement of gaze (Section 3.3.1) and gait (Section 3.3.2) behaviours. Section 3.4 illustrates the measurement of statistical analysis and the correlations between variables that this thesis would investigate are then explained in Section 3.5.

The methods to carry out the investigation are described in Sections 3.6 to 3.11. This begins with the recruitment of and criteria for participants in the experiment (Section 3.6), followed by the location where the experiment took place and the set-up in the laboratory (Section 3.7), the description of the protocol (Section 3.8) and the detail of the instrumentation for the experiment (Section 3.9). Section 3.10 explained the methods for instrumentational and data synchronisation consisting of hardware (Section 3.10.1), software (Section 3.10.2) and data synchronisation (Section 3.10.3).

Finally the data analysis (Section 3.11) is described along with statistical tests (Section 3.11.1) and descriptive analysis used in this thesis (Section 3.11.2). Conclusions of this chapter are presented in Section 3.12.

3.1 Development of parameters

This section explains the parameters developed for measuring the gaze and gait behaviours during walking. Firstly the preparation phase in which the behaviours would be recorded is defined (Section 3.1.1), followed by parameters in *Required Capabilities* (Section 3.1.2), *Provided Capabilities* (Section 3.1.3) and interested age groups (Section 3.1.4).

3.1.1 Preparation phase

When encountering a step-height in the pedestrian environment, the visual information of the step-height is received by the individual for the preparation of upcoming negotiation. The individual needs to see 'vision', not as something the individual does actively, but which is the means by which the brain receives its visual data about the environment around it. This turns around the normal way we tend to think about vision so that the question arises that the environment needs to communicate with the brain of the individual in order for the brain to figure out what to do about it (Tyler, In press).

Chapter 2 showed that the current best practice for the pavement design lacks scientific investigation into the capability of older people and the perception of the footway environment was rarely studied. It would be sensible for this thesis to start with understanding the individual's visual perception of a step-height on the pavement and the gait adjustments made as a result of the input of visual information. The individual's awareness of the footway environment might be reflected by visual and/or physical reactions to the step-height, showing how well the individual is able to prepare for the coming negotiation.

The process of walking on the pavement could be roughly divided into three phases: preparation, encountering and recovering (see Figure 3-1). The encountering phase has been widely discussed in studies in obstacle clearance but the way the individual adjusts and plans gait for the upcoming obstacle was rarely explained. The preparation phase means that in this phase participants are preparing themselves to overcome upcoming step-heights. The behaviours demonstrated in the preparation phase could reflect the individual's sensory perception and physical capability to the footway environment, which could imply the potential risk in the environment. In addition, the result would further suggest an accessible environmental setting for pedestrians of different needs.

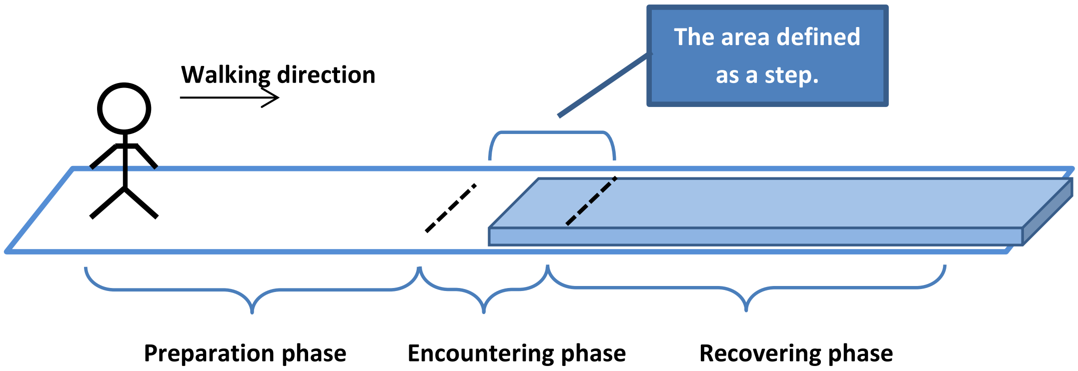


Figure 3-1: Three phases in negotiating an obstacle/hazard on the walkway.
1) Preparation phase: the individual plans footsteps after sensing the obstacle; 2) Encountering phase: the individual passes the obstacle; 3) Recovering phase: the individual recovers from the disturbance caused by encountering the obstacle and then adjusts back to normal walking.

The common step-heights on pavements are kerbs and unevenness resulting from subsidence or raising of a section which might be caused by a defect in installation, movement over time, the pavers themselves or tree roots and they are encountered by pedestrians on a daily basis. However, not all of the step-heights allow the individual enough time to process the visual information and adjust the gait pattern accordingly. It would be valuable to understand how and when the visual information of the step-height is perceived and the gait adjustment is made. The step-heights chosen for this study are commonly seen and negotiable for most pedestrians in the footway environment and comparing several difference step-heights at the same time would enable us to understand the scale of the effect of step-heights on sensory and physical capabilities and whether these two capabilities contradict, compensate or complement each other.

Previous studies in walking or obstacle clearance mainly centred on the encountering phase, and the overall behaviour performed when the individual approaches the obstacle during the preparation phase was rarely discussed. However, the performance during the encountering phase may well depend to a great extent on what happened during the preparation phase so it is necessary to start the investigation rather earlier in the approach process, i.e. during the preparation phase.

The start of the preparation phase is considered to be once the regular stride pattern has been attained – generally after the second stride has been completed. The preparation phase ends at the start of the encountering phase, which is taken to be one stride before the obstacle. During the course of the preparation phase, an important point is the first fixation on the obstacle, as this indicates that the brain is made aware of the possibility of the existence of the obstacle, and this is defined by a gaze attribute; the nature of the preparation is observed in how the gait pattern is affected by the perception of the upcoming obstacle. To define this point it is necessary to record gaze from the beginning of the preparation phase, and to compare any changes in gait during the preparation and encountering phases it is necessary to record both the gaze and gait variables and the interactions between them, starting some distance in advance of the obstacle and continuing as the individual approaches and encounters the obstacle.

It is necessary in order to understand the correlation between vision and feet movement, gaze and gait variables demonstrated in the preparation phase would need to be measured, synchronised and analysed both individually and in combination. In addition, given the novelty as well as the complexity of the collaboration of different instrumentation systems, the synchronisation of instruments used for recording and analysing the behaviours performed in the preparation phase is also one of the main outcomes of this thesis.

This thesis defines the preparation phase as the distance between two strides after the individual starts walking and the last stride before the individual encounters the step-height. The length of the preparation phase varies between individuals but based on the pilot experiment conducted prior to the full experiments of this thesis as well as previous research, the distance should be sufficient enough to measure a representative number of gait cycles and visual fixations (for schematic diagram of the preparation phase for this thesis, see Figure 3-1).

3.1.2 Parameters in Required Capabilities

Two footway environmental factors are considered in this study, step-height and lighting level. Older people are less physically and psychologically able to overcome obstacles on the pavement due to age-related diseases and degeneration. However, as highlighted in Section 2.3, the current design guidelines do not fully entail the demand from older pedestrians. In addition, the places where falls were most likely to happen to older people were pavement, kerb and street (see Section 2.2.2.3), and the activities when older people were participating during falls were walking and going up or down change in levels on the pavement (see Section 2.2.2.3). Considering the most commonly seen change in levels on the pavement is kerbs and unevenness, and to retain a rigorous control over the environment in order to study the person-environment interactions, the approach adopted in this thesis was to represent these obstacles in the form of a single step-height in the course of an otherwise flat footway.

To the best of our knowledge, current design guidelines seldom mentioned any scientific justification of the regulation for designing kerb height, and the threshold of pavement maintenance also lacked a scientific background. The step-height of 30 mm was thought to be the threshold between moderate and severe defect on the pavement (Pickett and Gallagher, 2010), which could represent the threshold of risk of falling; the step-height of 125 mm was the minimum suggested height for kerbs (Department for Transport, 2005b). Even though kerb height was suggested to be designed between 125 and 140 mm, the height of 140 mm would be too close to the minimum suggested height for the riser of staircases of 150 mm, which might be closer to the physical capabilities required by stairs than step-heights.

As this thesis is the first study of its kind, an interval of 30 mm serves as a reference which could be further narrowed down in further research in order to pinpoint an exact step-height for a particular footway environment.

Unlike regulation for stairs, pavement design rarely gives suggestions for the dimension of the transition phase (similar to the going of stairs). However, the transition phase is crucial for the individual to make adjustments to their footsteps for overcoming the step-height as well as landing on the raised/lowered surface. Therefore visual fixations on the transition phase are of great importance to understand how the individual perceives the step-height and plan footsteps accordingly. The visual fixations on the transition phase reflect the visual information the individual needs during the encountering phase therefore the area containing the transition phase and the step-height could be defined as the area of interest for visual fixation of the individual (See Figure 3-1).

Given there is little information about the dimension of the transition phase for step-heights on the pavement, the regulation for stairs provided by the Building Regulations 2010 as well as defined by the Department for Communities and Local Government (2013) would serve as a reference to define the overall area of a step-height, which would be 400 mm. The length of 400 mm is as the maximum going for utility as well as general access stairs. Despite the fact that footway and stairs are different in terms of transition areas and the number of steps, 400 mm can be a sensible reference as a minimum transition phase as well as area of visual interest for fixation on the footways.

The second factor is the lighting level. With degenerated vision, older people might not be able to receive as much information of obstacles to plan their journey as younger people. Previous studies in walking as well as obstacle clearance were mainly conducted in daylight, but walking in night time could be even more dangerous for older people and they might demonstrate different coping strategy from walking at an adequate lighting level. Therefore two lighting levels were set up in this study, 200 lux and 4 lux simulating daytime and street lighting respectively. The lighting level of 200 lux white light which is the minimum acceptable level for steps and stairs, and 4 lux yellow light, which is within the recommended average illuminance level ranging between 3.5 lux and 10 lux for pedestrian areas (Department for Transport, 2005). It would be valuable to understand the coping strategy implemented by both young and old people not only in daylight but also at low lighting level. The low lighting environment might possibly stop older people from going outdoors at night.

We understand that there are more than just two environmental factors in the footway environment, such as sound and other fellow pedestrians, but as this thesis is the first study of its kind to simulate walking in the real footway environment, we started with the two most fundamental factors to understand how pedestrians perceive the visual information and respond accordingly. Other confounding factors can be excluded in the experiment by simulating the two factors in a controlled laboratory with only one single participant involved at one time.

3.1.3 Parameters in Provided Capabilities

In order to understand how much the individual's sensory and physical capabilities are required by the footway environment, we would need to study how the individual responds to the parameters in the footway environment (the detail of the parameters in *Required Capabilities* is described in Section 3.2).

While walking on the footway, information received by vision takes up the majority of the overall information needed for planning the route. This thesis is particularly interested in how the information about the environmental setting is visually perceived by the individual and whether the individual uses different coping strategies for different settings. The gaze behaviour could also tell us the awareness of risk on the pavement that the individual faces.

Different environmental settings might require different levels of sensory and physical capabilities to negotiate and the gait pattern would help understand how the individual adjusts the gait to overcome upcoming step-height in the footway environment. The gait adjustments made by the individual could also imply the potential risk posed by the environment. In order to understand how much of the individual's sensory and physical capabilities is required by the footway environment and also how much their capability could be provided, we would need to study how the individual's physical responds to the environment.

As the visual information plays a major part in walking, it would also be valuable and sensible to compare the gait pattern with the gaze behaviour in the same setting so that we would be able to understand the perception of the footway environment and the individual's capability to counteract the upcoming step-height. Previous research has shown that the correlation between eye movement and the feet placement was not only statistically significant but also more indicative than any other paired locomotive body parts (Hollands et al., 2004). For this reason, this study also develops an instrumentational synchronisation to specifically investigate how gaze behaviour would associate with the gait pattern.

3.1.4 Age groups

Previous studies indicate that older people have age-related disease and degenerated sensory and physical capabilities (see Section 2.2.1), which made them vulnerable in the footway environment. This thesis is particularly interested in the sensory and physical capabilities that older people are able to apply, but in order to understand further whether the demonstrated performance is only registered in older people or if it could also be revealed by younger people, people from both age groups would need to be recruited. In addition, the difference in *Provided Capabilities* between the two age groups could tell us how much capability that people of different age groups provide and how much difference the same footway environment could mean to different age groups in terms of the awareness of potential risks.

The research questions of this thesis (see Section 2.6) concern the issues that older people might have in the footway environment but in order to establish if the issues only happen to older people or they are prevalent across different age groups, a control group of young people is also needed. As young people would be more adaptive to and not be challenged by the footway conditions as opposed to older people, the results help understand what older people might or might not be able to achieve. Therefore this thesis has a cohort of interests and a control group.

Given this study is the first of its kind in investigating and comparing the gaze and gait performance in the preparation phase during walking, people recruited for both age groups would be generally healthy and have no serious physical or cognitive impairment.

3.2 Performance measurement

The performance of the two parameters in *Provided Capabilities* – gaze (Section 3.2.1) and gait behaviours (Section 3.2.2) – is defined as the individual's coping strategy in this thesis. The coping strategy means the individual's visual perception of the step-heights plus the gait adjustments to the footsteps. The implementation of the coping strategy reflects the achievability of walking in a given footway environment. The interaction between these two parameters is discussed as the change in gait performance in relation to the first visual fixation (Section 3.2.3).

3.2.1 Gaze variables

Six variables will be analysed to represent the gaze behaviour: number of visual fixations, mean fixation duration, total fixation time, total gaze time, the start of the total gaze time (as 'the early total gaze time' used throughout this thesis) and the end of the total gaze time (as 'the late total gaze time' used throughout this thesis). Fixation is defined as stabilised gaze on an object for 99 ms or longer (Hollands et al., 2002; Patla and Vickers, 2003, 1997).

The main component of the first three variables (number of fixations, mean fixation duration and total fixation time) is visual fixation and in this thesis our area of interest for visual fixation is the step-height. Visual fixation has been used as a proxy for pre-conscious awareness of obstacles (see Section 2.4.3.3) and therefore is the main components of gaze analysis. In this thesis, the performance of visual fixations shows how an object draws the individual's attention, which could also be interpreted as the amount of information required to detect and measure the object. The information derived from visual fixations help the individual plan footsteps either consciously or subconsciously while walking in the preparation phase.

The number of fixations in this thesis means how many times the individual fixated the gaze on the step-height, which means how many times the individual returns the gaze in order to check the dimension of the step-height, so the number of fixations could also reflect the concerns the individual has over the step-height. The higher the number of fixations registered, the more concerned the individual feels about the step-height.

Mean fixation duration reflects how long on average each fixation is performed. During each fixation, the individual is processing the visual information for measuring the step-height. It also reflects the amount of visual information demanded by the individual to process the visual fixation. The longer the mean fixation duration is, the more hazardous (inconspicuous and/or uncompromisable) the step-height might be.

The total fixation time means the aggregation of all fixation durations in one trial. The aggregative time period indicates the total amount of time that the individual needs to check, calculate and measure the step-height. In comparison to the mean fixation duration, the total fixation time reveals the overall visual information required by the individual regardless of number of fixation or mean fixation duration. It reflects the overall visual awareness caused by the step-height. The longer the total fixation time is, the more visual attention the individual pays to the step-height.

The total gaze time is represented by the time period between the start of the first fixation and the end of the last fixation. In this period, the individual not only has to process the visual information but also reacts to the information with gait adjustments. The individual might gaze back for more information about the step-height and in the meantime adjust their gait pattern, so that it is an in-line coordination time for visual information, feedback and gait movement. The longer the total gaze time is, the longer the time the individual needs to integrate the perceived information along with cognitive as well as physical responses.

The early total gaze time is represented by the start of the first visual fixation, showing the moment when the individual starts fixating the gaze on the step-height. Different experiment settings might raise the individual's visual awareness to different levels and the start time might indicate the visibility of the step-height at a given lighting level. Difference in the sensory capability of different age groups could also associate with the early total gaze time. The later the gaze initiates, the less amount of time is allowed for reaction as well as response.

The late total gaze time is represented by the end of the last visual fixation, showing the moment when the individual finishes the fixation on the step-height. The late total gaze time indicates the concentration that the individual needs for acquiring visual information (Young and Hollands, 2010), which is associated with the individual's sensory capability and is also affected by the experimental setting. As this thesis excludes other confounding environmental factors by conducting the experiment in a controlled laboratory and simulating the pavement with only one step-height at one lighting level at a time, the late total gaze time might suggest the concentration solely for the individual to plan to overcome the step-height, which could reflect the individual's capability to cope with the step-height in the footway environment. The later the late total gaze time ends, the more aware the individual feels towards the step-height and also the more visual information the individual needs to make gait adjustments.

3.2.1.1 Gaze matrix

The study of gaze behaviour is normally undertaken with a view to understanding the function of the eye. In this thesis, however, the interest is focused on the environmental attributes and thus gaze behaviour is seen as an indicator of how the vision system is regarding the immediate environment. This is considered in terms of the number of times the eye fixates on a particular element of the environment and the length of time it does so. These two variables give rise to four possible categories of response: many short fixations, few short fixations, many long durations and few long durations. A matrix, designed for this thesis, consisting of the two gaze variables, the number of fixations and mean fixation duration, is plotted for two age groups separately to ease discussion of the gaze behaviour (see Figure 3-2).

All step-heights are grouped under the four categories defined by the attribute in relation to the mean value of the two gaze variables. More fixations with longer duration suggests that the response to the environment is that more time needs to be spent observing it (High-Attention Group). More fixations with shorter duration suggest that the response is that it is necessary to make several checks that the original interpretation continues to be corrected (Checking Group). Fewer fixations with longer duration suggests that the environment appears difficult to interpret and so more time needs to be spent calculating the appropriate action (Calculating Group). Finally, fewer fixations with shorter duration suggests that the environment has not warranted a lot of attention (Low-Attention Group).

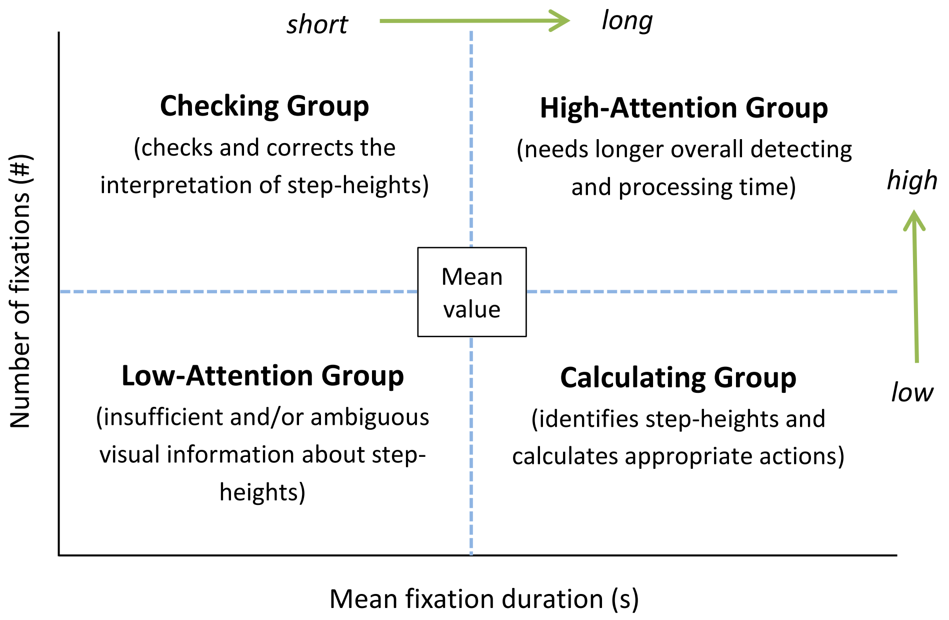


Figure 3-2: Gait matrix.
Four categories of visual behaviour divided by the mean value of the number of fixations and fixation duration

Step-heights falling into the High-Attention Group demanded the greatest overall detecting as well as processing time, which might reflect either the increased information processing in figuring out a subtle, low contrast step-height or planning to encounter a step-height exceeding lower limbs’ elevation (Patla and Vickers, 1997). On the contrary, step-heights in the Low-Attention Group might suggest a lack of visibility to the participants (Miyasike-daSilva and McIlroy, 2012). Previous studies in walking on stairs revealed that because of higher visibility of ascending than descending staircases, the importance of visual information of ascending staircases might be overestimated (Otter et al., 2011; Miyasike-daSilva et al., 2011; Miyasike-daSilva, 2011; Zietz and Hollands, 2009); however, as this thesis investigates the effect of lighting level on gaze behaviour, the availability of visual information provided by step-heights in different directions (ascending and descending) at different lighting levels might reflect the amount of visual information participants could possibly detect as well as perceive. Step-heights providing insufficient and/or ambiguous visual information might be a potential risk of falling as they are less likely to be detected, or, if detected, might evoke an incorrect response.

Neither Checking nor the Calculating Groups have been fully discussed in previous studies (see Section 2.4.3), but these two groups could still be defined by the attributes of gaze variables of number of fixations and mean fixation duration. Step-heights in the Checking Group might be too high to overcome by lower limbs, therefore causing the number of fixations to increase. However, the mean fixation duration for the Checking Group suggest they demanded shorter time for processing visual information. It could be the case that participants spent fixations on checking the step-heights in comparison with their own physical capability of footstep adjustments.

The Calculating Group reflects that increased time might be needed to identify step-heights which could be either so steep or so subtle that participants made longer fixation duration for calculating the visual information received. But the heights in the Calculating Group might be less physically challenging than in the Checking Group in terms of footstep adjustments.

3.2.2 Gait variables

Temporal gait performances of double support time, stride time, stance time and swing time from the way the individual walks are considered as the possible indicators of the risk of falling and the variability of these four variables could further demonstrate the individual's balance mechanism. These parameters performed in the preparation phase would be able to explain the scope of the impact of the environmental factors on the coping strategy adopted by the individual when planning to overcome the upcoming step-height. These four gait variables are the essential temporal gait events, and it is the collaboration between these variables that the individual could perform gait coping strategy.

Double support time is the time period when both feet are in contact with the floor in one single gait cycle. Double support time is widely used to imply the balance mechanism of the individual. Double support time may also reveal the risk of falling/tripping in the footway environment. The longer the double support time is the worse the balance mechanism the individual might have or the more aware the individual feels. A short double support time might imply a faster walking speed.

The stride time is the duration between the first initial contact (or heel strike) of one foot (either right or left) and the next initial contact of the same foot. A stride consists of stance time (when the foot is in contact with the ground) and swing time (when the foot is off above the ground), accounting for 60% and 40% respectively, though the ratio varies between individuals. Despite the fact that this thesis does not include spatial gait variables, stride time would still be able to imply the walking speed by being discussed alongside with other temporal gait variables.

A stride is equivalent to a gait cycle, and therefore stride time is the same as the gait cycle duration. For the sake of the analysis as well as discussion in the study, in the following sections and chapters, we used stride time for gait analysis and gait cycle for describing general spatial gait elements.

The stance time investigated in this study was calculated based on the equation suggested by Kirtley (2006), that is *stance time = (double support time + 100) / 2 (unit: millisecond)*. Stance time is also considered to be another indicator for balance mechanism. The increase in stance time as well as double support time suggests an increased overall support time, and on the contrary, the decrease in stance time as well as double support time might suggest a faster walking speed. Stance time is also used to calculate swing time in this thesis *(swing time = stride time – stance time)*.

Swing time is the time period when the foot is moving from toe off to the initial contact. During this period the foot is being trailed by the individual in the air without any ground contact. Stance time and swing time constitute stride time so these three variables actually consist of double support time. The swing time would be able to imply whether the individual made a longer or shorter step though the implication needs the supplementary information about the performance of the other temporal gait variables in this thesis.

The gait variability (represented by standard deviation and coefficient of variation) is also an indicator of the individual's balance mechanism. To the best of our knowledge, there has not been established significant clinical meaning of the gait variability (Hausdorff, 2005); however, by comparing the gait variability of each gait variable in each experimental setting, across all step-heights and at all lighting levels, we would be able to have an idea about the scale of effects as well as disturbances the environmental factors have on the gait stability. The greater the variability, the greater the disturbance the individual might experience.

3.2.3 Change in gait pattern associated with the first fixation

The association between sensory and physical capabilities cannot be established without their performance being analysed with synchronisation and by doing so, the influence of each variable on one another can be investigated. The synchronisation of the performance of gaze and gait parameters as well as the performance in relation to the environment settings is one of the objectives rarely dealt with in previous studies. As visual information plays a key role in walking, the correlation between gait performance and gaze behaviour in different phases, such as before and after visual fixations, is worth investigating.

As the fixation reflects the visual awareness caused by the footway environment, the initial occurrence of the fixation might trigger the process of visual information and consequently the gait adjustment will be made. Therefore the gait pattern after the first fixation would start to be affected by the received visual information.

The change in gait pattern in this thesis is defined as the difference between the gait pattern before and after the first fixation in the preparation phase. The preparation phase is divided into two parts – Phase One and Phase Two, separated by the first fixation – the gait pattern before the first fixation is defined as Phase One whereas the gait pattern after the first fixation is Phase Two. The difference was calculated as the mean value of each gait variable in Phase Two minus the mean value in Phase One (see Figure 3-3).

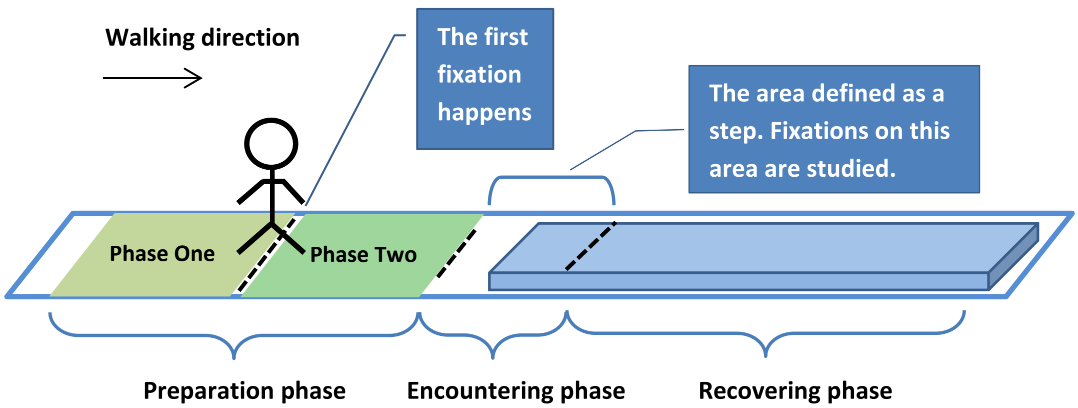


Figure 3-3: The schematic diagram of the relationship between first visual fixation and gait patterns.

There might be more than one visual fixation in each walking trial and the change in gait pattern might be varied by different fixations. However, as the number of strides and the number of fixations also vary between individuals, this thesis only centres on the change in gait variables associated with the first visual fixation, and the result would be regarded as a start point for any further investigation in the gait adjustment in relation to the sequence of fixations.

3.3 Scope of the measurement

The individual's sensory and physical capabilities would be measured by instrumentation. The capability of the devices used to measure the sensory capability of gaze behaviour (Section 3.3.1) and the physical capability of gait pattern (Section 3.3.2) is detailed.

3.3.1 Sensory capability - gaze behaviour

Various types of eye tracker have been used in gaze studies and the most commonly used yet traditional type is the monocular eye tracker. However, monocular eye tracker has its limits in the accuracy of recording especially in a dynamic environment due to parallax. The new type of binocular eye tracker has been developed to improve the defect caused by parallax. The experimental setting in this thesis would stimulate the dynamic footway environment, and therefore a wearable and mobile eye tracker would be considered. The SMI system (SensoMotoric Instruments Inc.) is reckoned to be capable of functioning with binocular recording in a dynamic environment.

Previous research has established that the sampling frequency of 30 Hz was sufficient enough to capture the gaze fixation (Patla and Vickers, 1997). As this thesis would only take into account the fixation rather than saccade, the 30 Hz sampling frequency would be regarded as a sufficient frequency.

3.3.2 Physical capability - gait pattern

The analysis of temporal gait parameters is crucial for understanding coping strategies used by the individual. Force platforms have been the gold standard method for detecting gait events with remarkable accuracy, however, the instruments are restricted to a static laboratory setting with a limited number of strides. Alternative methods or portable instruments have been developed and evaluated in gait analysis, and among them, the F-Scan system (Tekscan Inc.) provides a mobile solution that allows temporal parameters of each gait cycle to be recorded. The F-Scan system consists of shoes fitted with insoles which incorporate pressure sensitive sensors.

There are drawbacks to this method of measuring gait characteristics. First, absolute values of forces or pressure measured by the F-Scan system may be affected by high-pressure areas due to creases and crinkles in the pressure-sensitive material

(Catalfamo et al., 2008). Second, variation exists between participants and types of shoes they wear. Third, as with the static force plates, the system only provides data about the foot when it is on the ground and provides no information about the movement of the foot between stance phases. Fourth, the system only measures the ground reaction force, which is only one of the three directions of forces the individual received while walking. Despite these drawbacks Mueller and Strube (1996) concluded that force measures during walking from the F-Scan system and force platforms were highly correlated in a linear fashion, and a mean of three consecutive steps taken within a trial demonstrated reliability of peak plantar measures. Therefore F-Scan is most suited to studies which need to measure within-participant changes in gait parameters in a dynamic experimental setting.

3.4 Statistical measurement

The mean value is used to represent the performance of each gaze and gait variable. The mean value of each gaze and gait variable in each trial is analysed and discussed in relation to each environmental setting.

In previous studies of gaze behaviour, the proportion of fixation durations to the total gaze time in an experiment trial seems to be used more often than the absolute time period in previous research (Miyasike-daSilva et al., 2011). However, this thesis is interested in the absolute amount of time the individual requires to process visual information so that we would be able to understand the time period the individuals might need to sense the step-height as well as to coordinate gait adjustment. The absolute time period might help understand the time the individual needs to navigate in the footway environment.

Mean value in gait analysis has been widely used to represent the individual's gait pattern. Standard deviation and coefficient of variation have been commonly used to represent gait variability. To the best of our knowledge, standard deviation and coefficient of variation did not have significant clinical differences and there was hardly any clinical threshold for gait analysis (Wurdeman et al., 2012). Therefore both parameters will be examined in this thesis.

In addition to gait and gaze behaviours, the association between the individual's physical characteristics and each gait and gaze variable would also be examined. As this thesis does not centre on the age-related difference in sensory as well as physical capabilities between young and older age groups, the analysis for this association will be just to understand any possible clustering outcome that could represent particular sensory or physical characteristics correlated with the *Provided Capabilities*.

3.5 Correlation between variables

This thesis centres on the individual's sensory and physical capabilities in relation to the capability required by the footway environment. The correlation between each variable (either gaze or gait) and each experimental setting (a given step-height at a given lighting level) will be analysed by statistical tests elaborated in Section 3.11.

In order to respond to the research questions set out in Section 2.6, each of the gaze variables (number of fixations, mean fixation duration, total fixation time, total gaze time, the early total gaze time, the late total gaze time), gait variables (double support time, stride time, stance time and swing time) and their variability (standard deviation and coefficient of variation) and the change in gait variables associated with the first visual fixation (double support time, stride time, stance time and swing time) will be analysed statistically for each experimental setting (-125 mm at 200 lux, -90 mm at 200 lux, -60 mm at 200 lux, -30 mm at 200 lux, +30 mm at 200 lux, +60 mm at 200 lux, +90 mm at 200 lux, +125 mm at 200 lux, -125 mm at 4 lux, -90 mm at 4 lux, -60 mm at 4 lux, -30 mm at 4 lux, +30 mm at 4 lux, +60 mm at 4 lux, +90 mm at 4 lux, +125 mm at 4 lux. Detailed set-up and protocols are explained in Section 3.7 and 3.8). In each experimental setting, each environmental factor (step-height and lighting level) will be statistically tested both individually and interactively with one another. The trial effect will also be examined. (In order not to make confusion about the directions of step-heights, ascending step-heights are presented with the '+' symbol, i.e. +30, +60, +90 and +125 mm whereas descending step-heights with the '-' symbol, i.e. -30, -60, -90 and -125 mm, throughout this thesis.)

In addition to the analysis of the correlation between gaze and gait behaviours, the association between the individual's physical characteristics (age, sex, whether or not wearing glasses) and the sensory as well as physical performance will also be analysed.

All of the analyses mentioned above require detailed gaze as well as gait data, and in the following sections of this chapter, the protocol and experimental setting for recording the individual's physical performance along with data analysis will be elaborated.

3.6 Participants

Thirty four participants in total were recruited for this study with an equal number of young (25-34 years) and older (65-74 years) people. All participants had no previous balance, visual or cognitive impairments or other relevant medical conditions. All participants had no difficulty walking 800 m (or half a mile). Young participants were recruited via an email sent out to all students in the Department of Civil, Environmental and Geomatic Engineering at University College London. Older participants were recruited via a revised email sent to all students and staff at UCL as well as to those who were aged 65-74 in the participant database of PAMELA (Pedestrian Accessibility Movement Environment Laboratory, UCL). Lord and colleagues (2007) pointed out that there had not been consistency in the definition of the older person, and the most commonly used definition is people aged 65 years and over with the subgroups of 65-74 years, 75-84 years and 85 years and older. Being the pioneering investigation in studies of this kind, this thesis is interested in older people aged 65-74 as the baseline performance of healthy elderly. This approach was approved by the UCL Research Ethics Committee.

All participants were provided with an information sheet upon their arrival and a signed consent form was returned once they agreed to take part. All participants then took the mini-mental state examination (MMSE) to screen whether they were exempted from any cognitive impairment, and the Fall Efficacy Scale International (FES-I) to measure the degree of their fear of falling. Participants were eligible to be finally recruited only with an MMSE score greater than 25 (Beauchet et al., 2007) and FES-I score lower than 24 (Delbaere et al., 2010), ensuring that they were capable of participating in experiments.

The Clinical Knowledge Summaries (2012) suggests screening tools of 180° turn test and Timed Up and Go test (TUG) as clinical fall risk assessment tools. The 180° turn test requests each participant to stand and step halfway around (180°). The number of steps each participant makes is recorded. TUG test requests each participant to stand up from a chair without any external aids, walk 3 metres at usual pace, turn around, walk and sit back down. The time for completing the test is recorded. Those who had any known balance or visual impairment affecting their gait and posture, or made the 180° turn test with more than 5 steps, or completed the Timed Up and Go test (TUG) with more than 13.5 sec were considered to have higher risk of falling and therefore would be excluded from experiments.

Participants also took the binocular Pelli-Robson contrast sensitivity test (Pelli et al., 1988) to ensure there was no visual impairment affecting contrast detection, given the step-heights commonly seen on the pavement are often detectable by the contrast between paving slabs (see Section 3.1.2). Those who scored lower than 1.65 in the Pelli-Robson test would be also excluded.

Some basic information as well as the physical characteristics were also measured and recorded, including participants' height and weight, self-reported falls history within the past 12 months, activities level and walking speed (by 10 steps walk) to provide a set of battery information for subsequent reference.

3.7 Location and experiment set-up

A walkway of 16.8 m by 1.2 m was set up at PAMELA of the ARG (Accessibility Research Group) at UCL. The walkway surface was standard concrete chamfered pavers reproducing generic footways in the UK, and walled by blackout cloth and screens to exclude surrounding distractions within the laboratory. The width of 1.2 m was wider than the suggested 0.7 m for a single ambulant person and even reached the minimum suggested width of 1.2 mm for two ambulant people or a visual impaired person being guided (Department for Transport, 2005). This was so that the participants would not feel constricted by the available width of the walkway. The walkway consisted of fourteen 1.2 m by 1.2 m modules which could be raised or lowered to specific heights (see Figure 3-4, 3-5 and 3-6). A step-height was set up at a point 2.4 m before the end of the walkway for each walking trial in order to maximise the length of the effective preparation length, yet ensuring that the length of the walkway after the step-execution would still be sufficient enough to make complete finishing footsteps without disturbing gait cycle before and/or during the step-execution. This was so that the participant's encounter with the height change was not influenced by the sight of the end of the walkway. A starting line was set up at a point 1.2 m from the start of the walkway, making it an overall 13.2 m effective walking distance to establish the preparation phase. In the pilot study of this experiment, we found that a preparation phase of 5 m was not long enough to demonstrate gait cycles for analysis so the preparation phase was extended to 13.2 m. Previous research revealed that individuals fixated their gaze on potential risks two steps ahead while walking (Marigold et al., 2006; Patla and Vickers, 2003) and therefore the 13.2 m for preparation phase was sufficient enough to register an individual's gait and gaze behaviour.

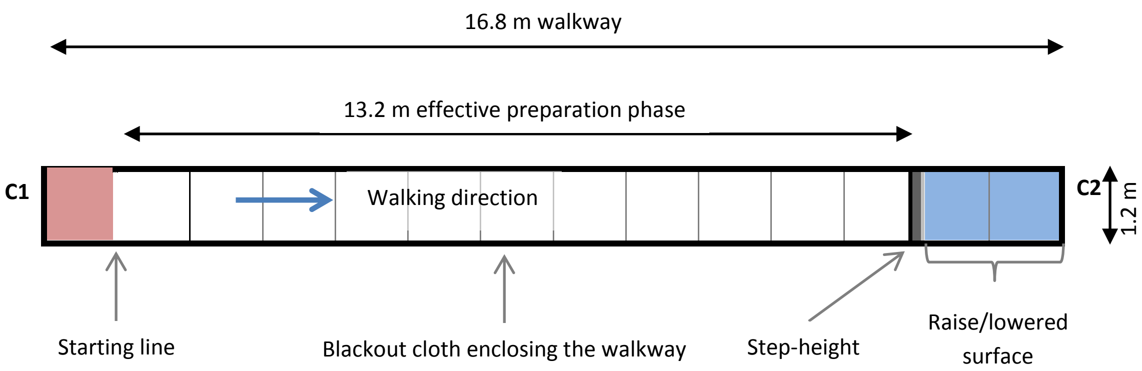


Figure 3-4: Bird's eye view schematic diagram of the experimental set-up in the PAMELA facility.

Each square constitutes one module (1.2 m X 1.2 m).
C1 and C2 represent the locations of two fixed cameras.

Figure 3-5: Screenshot from camera C1 (indicated in Figure 3.4)

Figure 3-6: Screenshot from camera C2 (indicated in Figure 3.4)

The real pedestrian environment was taken into account by reproducing step-heights of 30 mm, the threshold between moderate and hazardous defects on the pavement (Murray, 1967), and 125 mm, minimum height of a standard kerb (Department for Transport, 2005), and also an interval about 30 mm between the two heights on walkways. Each step-height was arranged and positioned along the final 2.4 m of the walkway by raising or lowering the height of the modules to 0 mm, 30 mm, 60 mm, 90mm and 125 mm.

The experiment was conducted at two designated lighting levels: 200 lux white light, which is the minimum acceptable level for steps and stairs, and 4 lux yellow light, which is within the recommended average illuminance level ranging between 3.5 lux and 10 lux by the Department for Transport (Department for Transport, 2005), and between 2 lux and 15 lux by European Standard EN 13201-2:2003 (British Standards Institution, 2003) as well as British Standard BS 5489-1:2003 (British Standards Institution, 2012) for pedestrian areas. During the course of the experiment, the average illuminance levels measured by Konica Minolta Illuminance Meter T-10 at the surface level of the modules were 294.18 lux and 5.32 lux respectively. Both the measured illuminance levels are within suggested lighting levels by official guidelines.

3.8 Protocol

Participants were asked to walk down the walkway at a self-selected pace and in the way they normally walked in the footway environment. The experiment consisted of two parts: 1) a pre-experiment in which three walking trials were performed by the participants to familiarise themselves with the environment. For each participant, the leading foot constantly used in these trials was then requested to be used throughout the course of experiments for the consistency in data analysis; 2) In the experiment itself, participants were asked to walk up and down the walkway encountering each step-height at the lighting level of 200 lux and then to repeat the experiment at the lighting level of 4 lux. The order of the step-heights was randomly arranged but for each setting (one step-height at one lighting level) three consecutive walking trials were performed. Participants were never told which step-height to expect on the walkway.

Although the more trials there were, the more statistically significant the results would be, the fatigue might wear out participants' physical strength and there was a risk that they could respond differently as they learn the details of the walking route too well and adjust their approach accordingly, which could offset changes in gaze and gait behaviours with relation to environmental factors. This thesis centres on participants' reaction to a given environmental setting for which they could not have planned, in order to investigate how they would cope with it. The trial effect should be limited by randomising the order of the step-height as well as limiting the number of trials.

For each trial, participants stood right behind the waiting line and were asked to look at the triggering box of the F-Scan insole sensors system (Tekscan, Inc.). Participants started each walking trial when the light bulb on the triggering box was activated. Once they reached the end of the walkway, a verbal signal of 'STOP' was given for signalling the end of data recording. After three consecutive trials for each setting had been completed, participants had a minimum 5 minute break before taking part in the next setting. In the meantime a new step-height was arranged. Considering the number of trials and the individual's physical condition, each young participant was requested to stay at PAMELA for either 2 days with 2 hours for each day or one day with 4 hours plus a minimum 30 min break between two sessions of different lighting levels; by contrast, each older participant was requested to stay at PAMELA for 2 days with 2 hours for each day. Potential fatigue was an issue – in all, a participant would be walking around 750m to complete the experiment, which is rather more than many of them, especially the older participants, would manage in a normal day.

3.9 Instrumentation and data acquisition

The eye tracker and plantar force measurement system were used to capture gaze fixations and gait data (see Figure 3-7). The binocular SMI GazeWear (SensoMotoric Instruments Inc.) eye tracking system with a sampling frequency of 30 Hz was calibrated through the standalone software and worn by each participant. The mobile eye tracking data recording unit were attached to each participant's waist. A pair of F-Scan insole sensors was trimmed to fit into each participant's shoes, connected to the wireless unit and calibrated through the standalone software. Participants were requested to wear flat shoes to keep crinkles and creases in the insoles to a minimum level. Raw data of the plantar force was recorded with a sampling frequency of 50 Hz.

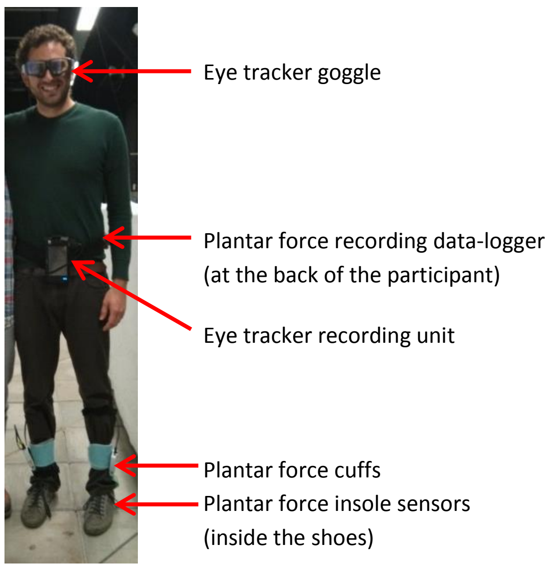


Figure 3-7: Devices used for collecting gaze and gait data in the experiment.

For recording the overall time spent on each trial for each participant, a bespoke light gate was installed to log the timestamp when the participant passed through the step-heights, signalling the completion of gaze and gait behaviours in the preparation phase.

The light gate consisted of a set of retroreflective sensors and reflectors set up at 56.5 cm, about individual's knee height, above the level of the preparation phase walkway, right above the transition area between the raised or lowered surface and the surface of preparation phase. Data received from light gate was recorded by Labview 2013 (National Instruments) with a sampling frequency of 1000 Hz.

A high-definition camera (Logitech HD Pro Webcam C920) was set up at each end of the walkway to capture the number of gait cycles as well as the stepping foot (see Figure 3-4, 3-5 and 3-6 for the locations of cameras as well as screenshots from videos).

3.10 Instrumentational and data synchronisation

To the best of our knowledge, previous research hardly synchronised the measurement of the gaze behaviour with gait pattern over a long walking distance to understand participants' physical response when approaching obstacles. Therefore the synchronisation of instrumentation in this thesis was further detailed in hardware (Section 3.10.1), software (Section 3.10.2) and data synchronisation (Section 3.10.3).

3.10.1 Hardware synchronisation

The hardware synchronisation was the backbone of data recording in this thesis. For each trial, the recording process began with starting up the video recording, followed by the eye tracker system. As the eye tracker could not be synchronised with either the F-Scan system or the light gate in terms of signal transmission, the only feasible way to log the timestamp of the start of F-Scan recording into eye tracking data was to use the field camera on the eye tracker to record the image of the light bulb being activated by F-Scan system. Therefore before each trial started, participants were asked to look at F-Scan's triggering box for recording the moment when the light bulb was activated. Follow-up software and manual synchronisations were then able to identify the timestamps registered by the activation of the light bulb in the video (see Figure 3-8). As the F-Scan system was more robust than the other devices in the experiment, the hardware synchronisation was built on the F-Scan system.

The light gate was synchronised with the F-Scan system by the digital input from the F-Scan's triggering box. When the F-Scan system started recording, a signal from the standalone software was sent wirelessly and simultaneously to both the insole sensors and the triggering box, and then the triggering box sent a signal to the National Instrument Module as well as the Labview (controlled on a laptop) through wires, signalling the start of the recording. When all devices were triggered and synchronised, participants started each trial when the light bulb was activated. When the trial finished, F-Scan stopped recording and in the meantime sent a signal to stop the recording of the light gate. The recording of eye tracker and video were then stopped manually and separately.

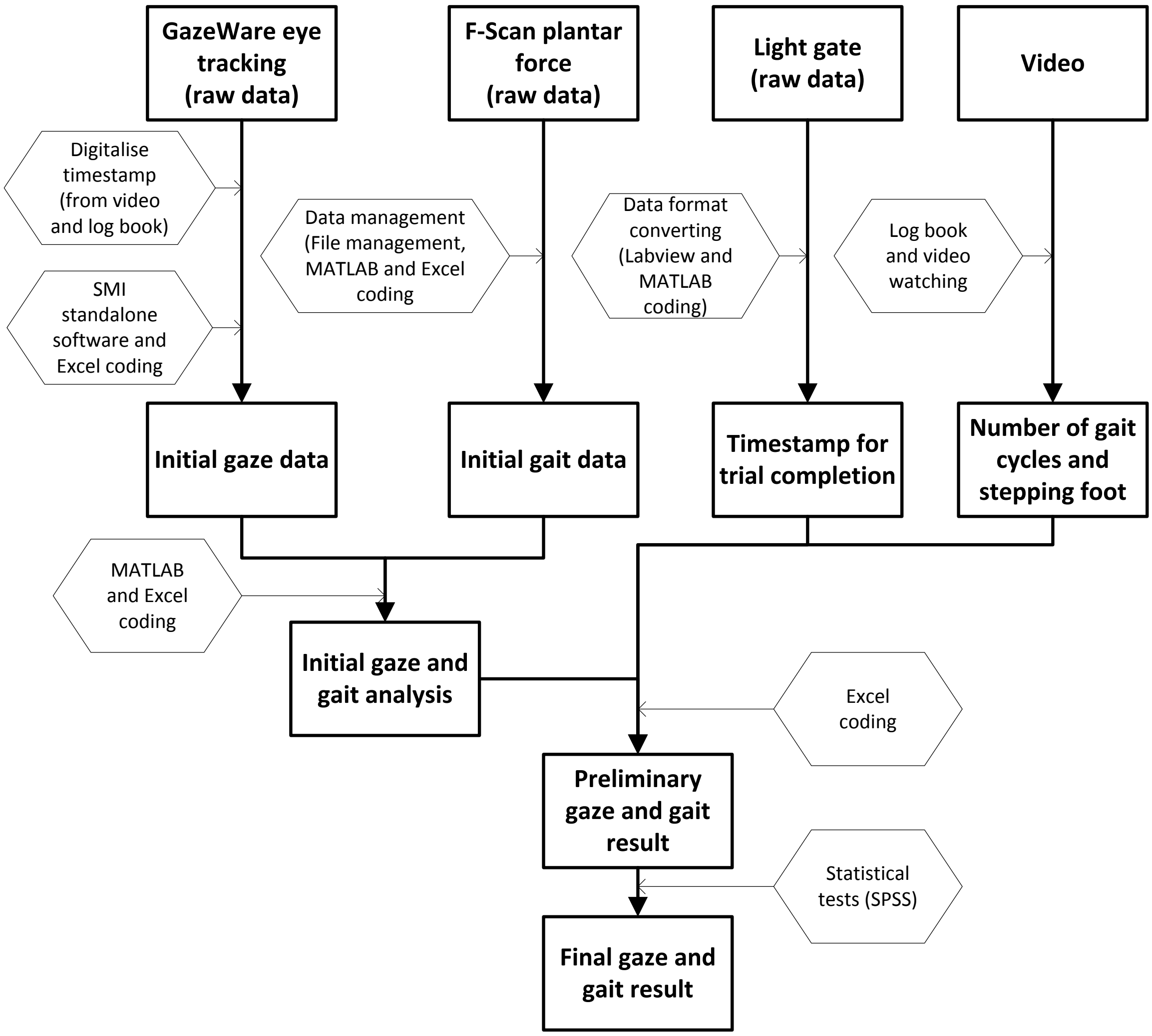


Figure 3-8: Flowchart of the process of data synchronisation and analysis.

3.10.2 Software synchronisation

Along with the hardware synchronisation, F-Scan system was also the foundation of software synchronisation (see Figure 3-8). As F-Scan and the light gate were synchronised, the same timeline was shared. The timestamp of the triggering signal from F-Scan system recorded by the field camera on the eye tracker was read with the corresponding timeframe in the video. However, as each device recorded data in different software – either a standalone package or bespoke software. Further data synchronisation in Excel 2010 (Microsoft Corporation) and MATLAB R2012b (MathWorks Inc.) was required.

3.10.3 Data synchronisation

The data recorded in this experiment were from four strands (see Figure 3-8). The eye tracking data was firstly analysed by its standalone software and then only the visual fixation information was used. The absolute timestamps of the visual fixation data were then offset by the timestamp logged by the triggering box in order to be synchronised with the timeline of the plantar force data. The raw plantar force data was exported directly from the standalone software. Both eye tracking and plantar force data was then initially paired as well as analysed in MATLAB. The light gate data was converted from Labview to MATLAB due to format compatibility and then on to Excel for further analysis. From the videos of each trial, the number of gait cycles and the stepping foot were identified, which further determined the number of gait cycles in the preparation phase performed in each trial. All of the output was eventually synchronised with the same timeline and saved in csv format.

3.11 Data analysis

In the main data analysis, a bespoke MATLAB script was used to process the gaze and gait data. The gaze variables extracted by the script were the number of fixations and mean fixation duration. The gait variables calculated and analysed by the script were double support time, stride time, stance time and swing time for each stride. The initial two strides as well as the stride during which participants were stepping over the step-heights were then eliminated from the analysis.

Bespoke codes written in Excel further calculated the total fixation time, total gaze time, the early total gaze time and the late total gaze time for gaze variables, and also mean value, standard deviation and coefficient of variation for each gait variable. The change in gait pattern associated with the first visual fixation (represented by Phase Two minus Phase One) was then analysed in Excel.

3.11.1 Statistical analysis

Given the complexity of the nature of the data sets, this thesis applied different statistical tests at different stages of analysis to investigate the association between variables and environmental factors. For each variable, a two-way analysis of variance and cluster analysis were performed. In addition, descriptive analysis was also carried out to explain noticeable results, given that this thesis has a relatively small sample size by which the significance of statistical analysis might be underestimated. For the intertwined attributes between the number of fixations and the mean fixation duration, the gaze matrix (see Section 3.2.1.1) was especially designed in this thesis for presenting the association between gaze variables and environmental factors.

3.11.1.1 Two-way analysis of variance

Before elaborating the statistical tests used in this study, all gaze and gaze variables investigated are revisited and listed as follows:

1) Gaze (in each trial): number of fixations, mean fixation duration, total fixation time, total gaze time, early total gaze time and late total gaze time.
2) Gait (in each trial): double support time (mean, standard deviation and coefficient of variation), stride time (mean, standard deviation and coefficient of variation), stance time (mean, standard deviation and coefficient of variation) and swing time (mean, standard deviation and coefficient of variation).

3) Change in gait patterns associated with the first visual fixation: double support time, stride time, stance time and swing time.

All of the statistical tests were conducted in SPSS v. 12 (IBM Chicago). For each variable, a two-way analysis of variance test was carried out for young and older participants separately. The environmental factors, step-height and lighting level, acted as fixed factors whereas each gaze or gait variable was a dependant variable. The sequence of trials was defined as a random factor as we were aware that trial effect might be a consequence of performing three consecutive trials for each setting. The trial effect would help understand how participants utilised the familiarity of the footway environment. The direction of the step-height, ascending and descending, was a second layer environmental factor to understand whether in general the direction of the step-height had any association with dependant variables.

Each data set was firstly tested for normal distribution in order to examine one of the assumptions of the ANOVA test. However, as most of the data sets violated this assumption, all data sets were plotted into histograms and normal Q-Q graphs to check the deviation from standard deviation. Previous studies in statistical analysis (Montgomery, 2009; Zar, 2010) suggested that if the violation is moderate, the data set is small and the assumption of homogeneity of variance is not violated. The ANOVA test is robust. Therefore the ANOVA test was still applicable in the present analysis instead of conducting a series of non-parametric test such as Wilcoxon signed rank test, which would lead to possible type I error. Only one data set was transformed by square root due to severe violation of the normal distribution condition.

In the two-way ANOVA test, significance levels were corrected by the Bonferroni adjustment and the Tukey's honest significant difference (HSD) was used to conduct post-hoc comparison tests among variables (comparison tests on step-heights between -125, -90, -60, -30, +30, +60, +90 and +125 mm; comparison test on lighting levels between 200lux and 4lux; comparison tests on the interaction between step-heights and lighting levels).

3.11.1.2 Cluster analysis

Even though this study centres on the visual perception and gait adjustments in the footway environment within each age group, the difference in the gaze and gait behaviour related to physical characteristics was also worth exploring as the participants could be easily categorised into subgroups by their individual's characteristics such as age, sex and whether or not they were wearing glasses. The data of each variable for both age groups as a whole underwent cluster analysis in order to test the association between individuals' physical characteristics and the performance of gaze and gait.

The *K*-means clustering was used for the cluster analysis and the Elbow Method (Ketchen and Shook, 1996) was used to determine the initial number of clusters. Then the number of clusters was narrowed down in order to find an optimal number of clusters in which the distribution of participants was less skewed. A chi-square test for independence was then applied to investigate the correlation between the clustering outcome and the physical characteristics of age, sex and glasses.

3.11.2 Descriptive analysis

The descriptive analysis was used to compare the outcome of the gaze and gait behaviours across all step-heights and lighting levels regardless of the statistical significance level. As neither the sample size nor the number of trials in this thesis was substantial, the statistical significance might not be significant even though some results could register a noticeable tendency. The result of each variable was compared as well as plotted across all step-heights in the ascending order, from -125 mm to +125 mm, so that the outcome could be visualised and discussed.

3.12 Conclusion

Based on the research questions defined in the Chapter 2: Background, this chapter defined the parameters, variables and the capability of measurement for answering the research questions. The experiment simulating the footway environment was carried out to observe the gaze and gait behaviour of both young and old participants. Data were recorded through bespoke synchronised instrumentation and then analysed with statistical tests. The validation of the instrumentational synchronisation and the results of statistical analysis will be presented in the next chapter.

Chapter 4: Instrumentational synchronisation validation and results of statistical analysis

Participants' physical information and the result of the screening as well as baseline tests showed that none of them had any known mobility, visual or cognitive impairment (Section 4.1). The synchronisation of the instrumentation was tested and validated throughout the experiment (Section 4.2). Six gaze variables (number of fixations, mean fixation duration, total fixation time, total gaze time, early total gaze time and late total gaze time) are analysed for young and older participants separately (Section 4.3). Four gait variables (double support time, stride time, stance time and swing time) are also analysed separately for both age groups. The mean value, standard deviation and coefficient of variation are investigated for each gait variable (Section 4.4). Finally, the change in all four gait variables associated with the first visual fixation is presented (Section 4.5). The results of the cluster analysis is described for each gaze as well as gait variable to associate the performance and the physical characteristics of participants. The results of all the statistical analysis are described in this chapter and the overall result and discussion of gaze behaviour will take place in chapter 6, gait pattern in Chapter 7 and the interaction between gaze and gait behaviours as well as the examination of current design guidance in Chapter 8.

4.1 Participants

Thirty-four participants were recruited initially for the experiment within which thirty-one participants provided valid data.

Fifteen were young participants aged between 25 and 34 with 7 males and 8 females (see Table 4-1). In order to understand how their subsequent performance in the experiment might be related to their individual characteristics, data were collected about these before the experiments started. The mean age of the younger group was 28.2 years with a standard deviation of 2.65 years. The average height of the young participants was 172 cm with a standard deviation of 8.38 cm. The average weight was 67.75 kg with a standard deviation of 14.48 kg. The average score of the Timed Up and Go (TUG) test for the young participants was 8.46 seconds with a standard deviation of

1.48 seconds. Ten steps of normal walking took them an average of 6.27 seconds with a standard deviation of 0.57 seconds, and the ten steps enabled them to cover an average distance of 7.34 m with a standard deviation of 0.34 m.

Table 4-1: Details and characteristics of young participants.

Young Participant ID	Age (years)	Weight (kg)	Height (cm)	180degree (steps)	TUG (s)	10steps (s/m)		sex
P22	33	47.9	169.5	4	8.9	6.6	7.28	F
P31	25	88.1	180.4	2	7.9	5.42	7.9	M
P32	26	69	179.4	4	12.43	6.1	7.66	M
P41	27	62	173.5	2	8.13	5.6	7.3	M
P42	28	46.5	167	2	8.7	6	6.9	F
P51	31	54	159.8	3	7.39	7.1	7.9	F
P61	27	74.2	170.5	3	10	6.1	7.4	M
P62	25	90.5	175.5	3	6.8	7	6.9	M
P71	26	63.25	165	3	7.8	6.5	6.7	F
P72	30	63.35	171	3	8.2	6	7.3	F
P81	33	63.55	165	3	6.2	5.7	7.5	F
P82	28	54.95	162	3	9	6.6	7.5	F
P91	28	85.1	184.5	4	9.6	6.3	7.1	M
P111	30	87	189	5	8.4	5.8	7.4	M
P101	26	66.9	168	4	7.48	7.3	7.3	F

Sixteen older participants were aged between 65 and 74 with an equal number of males and females (see Table 4-2). Mean age was 69.25 years with a standard deviation of 3.59 years. The average height was 169.25 cm with a standard deviation of 11.93 cm. The average weight was 75.60 kg with a standard deviation of 9.73 kg. The average score of the Timed Up and Go (TUG) test was 9.91 seconds with a standard deviation of 1.74 seconds. Ten steps of normal walking took an average of 5.77 seconds with a standard deviation of 0.57 second, and covered an average distance of 6.90 m with a standard deviation of 1.07 m.

All of the 31 participants had MMSE score higher than 25 and FES-I score lower than 23, indicating they had neither severe cognitive impairments nor excessive fear of falling. All of the participants completed the test of 180 degree turn within 5 steps and the Timed Up and Go test within 13.5 seconds, indicating they had a lower risk of falling. None of the participants reported any known balance or visual impairment affecting their gait and posture. The Pelli-Robson contrast sensitivity test showed no severe visual impairment in contrast sensitivity.

Table 4-2: Details and characteristics of older participants.

Older Participant ID	Age (years)	Weight (kg)	Height (cm)	180degree (steps)	TUG (s)	10steps (s/m)		sex
E11	68	80	181.5	4	11.8	6.6	7.2	M
E21	70	78	183.5	3	8.3	5.3	6.9	M
E22	69	87.2	181.5	3	11.5	5.9	6.8	M
E23	69	68.75	185	3	8.2	5.4	8.3	M
E31	74	67.05	172	5	12.1	5.6	5.8	F
E32	69	81.5	157	4	8.1	5.8	7.2	F
E33	70	69.85	165	4	9.6	7.3	6.8	M
E41	74	60.85	158	4	12	5.8	6.2	F
E42	70	74.1	174	3	8.3	5.8	7.5	M
E43	65	84.55	178	3	11.1	5.7	7.9	M
E51	65	89.5	185	4	7.4	5.9	9.4	M
E52	70	84.5	160	4	12.86	6.23	5.9	F
E61	65	61	159	4	8.8	5.4	7.3	F
E62	76	60.6	153.5	3	9.2	5.1	5.3	F
E71	67	81.3	154.5	4	9.1	4.96	5.6	F
E72	65	80.9	160.5	3	10.2	5.6	6.4	F

4.2 Synchronisation

This thesis designed instrumentation to synchronise the data of F-Scan plantar insole sensors, SMI GazeWear and a bespoke light gate system (see Figure 3-8). This ground breaking synchronisation enabled us to clearly define the preparation phase for gait analysis, the early and late total gaze time for gaze analysis and the change in gait pattern associated with the first visual fixation.

The synchronisation result can be explained by an example from Participant E41 traversing the footway which had been set up with a step-height of -30 mm at 200 lux (see Figure 4-1). The upper section of the graph shows the number of fixations (on the y-axis) against time (on the *x*-axis) so that it shows the duration for each fixation and when it occurred. The Total Fixation Time is the aggregation of individual fixation durations (this is the aggregation of the three individual fixation durations in this case).

The total gaze time is the time period between the early total gaze time and the late total gaze time (this is between the start of the first fixation and the end of the third fixation in this case). The early total gaze time is defined as the time period between the start of the first fixation and the participant passing through the light gate, demonstrating the time period participant had between their initial fixation and the completion of the trial. The late total gaze time is the time period between the end of the last fixation and the participant passing though the light gate, showing when the participant finally gazed away from the step-height.

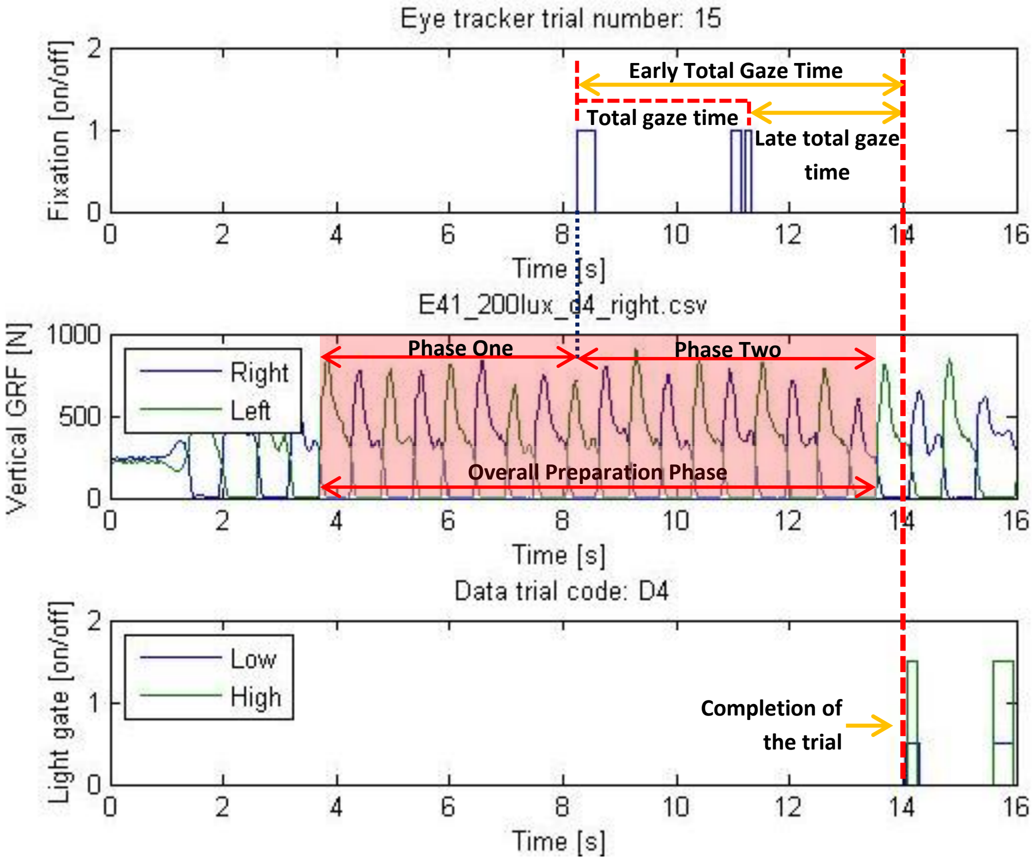


Figure 4-1: The synchronisation of data from plantar force, eye tracking and light gate with some temporal variables explained.

The middle section of the graph (see Figure 4-1) demonstrates the overall gait cycles taking place in this walking trial with 'Right' meaning right foot and 'Left' meaning left foot in the key. The ground reaction force represents the plantar force in Newton. The Overall Preparation Phase is defined as the period of gait cycles excluding the first two strides as well as the stride which occurred right at the step-height. The preparation phase is further divided into two phases. Phase One is defined as the part of the preparation phase prior to the start of the first fixation whereas Phase Two is the other part of the preparation phase after the start of the first fixation.

The bottom section of the graph (see Figure 4-1) shows the timestamp when the participant passed through the Lower Light Gate, showing the completion of the trial.

4.3 Gaze behaviour (sensory capability)

The analysis of all gaze variables, number of fixations (Section 4.3.1), mean fixation duration (Section 4.3.2), total fixation time (Section 4.3.3), total gaze time (Section 4.3.4), early total gaze time (Section 4.3.5) and late total gaze time (Section 4.3.6) will be elaborated in the following subsections.

4.3.1 Number of fixations

Young participants

There is a statistically significant main effect for step-height, F (7, 702) = 3.720, p = 0.001, with the effect size (Partial Eta Squared) of 0.36. Post-hoc comparison tests reveal that the number of fixations for +125 mm (M = 3.93, SD = 2.89) is significantly greater than -60 mm (M = 2.46, SD = 2.08), -90 mm (M = 2.48, SD = 1.98) each with p = 0.001. The main effect for lighting level (F (1, 702) = 2.826, p = 0.93) does not reach statistical significance. The interaction effect between step-height and lighting level is not statistically significant (F (7, 702) = 1.024, p = 0.413). Direction is a significant factor with F (1, 702) = 15.535, p < 0.001 and effect size of 0.021. Ascending step-heights (M = 3.41, SD = 2.66) result in more fixations than descending step-heights (M = 2.71, SD = 2.16) at p < 0.001 (see Table 4-3).

Older participants

There is a non-significant main effect of step-height as well as lighting level on number of fixations (F (7, 750) = 8.884, p = 0.518, and F (1, 750) = 0.020, p = 0.887, respectively). The interaction effect between step-height and lighting level is not statistically significant (F (7, 750) = 0.257, p = 0.970). The sequence of trials accounts for variance in the number of fixations with a statistically significant F (1, 750) = 11.263 at $p < 0.001$ and effect size of 0.27. The post-hoc comparison test reveals that the number of fixations for Trial One (M = 4.40, SD = 3.51) is significantly greater than Trial 2 (M = 3.58, SD = 2.79) and Trial 3 (M = 3.22, SD = 2.98) with p = 0.04 and $p < 0.01$ respectively. Direction has no statistical association with number of fixations with F (1, 750) = 2.462 and p = 0.117 (see Table 4-3).

Table 4-3: Mean number of fixations (unit: count).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	3.01	2.49	2.47	2.86	3.01	3.39	3.31	3.93
Old	4.12	3.76	3.78	3.95	3.81	3.54	3.20	3.74
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	2.56	2.18	2.36	2.73	3.36	3.31	3.27	3.51
Old	4.24	3.84	3.84	3.86	3.59	3.75	3.06	3.80
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	3.47	2.80	2.58	2.98	2.67	3.47	3.36	4.36
Old	4.00	3.61	3.73	4.04	4.04	3.33	3.33	3.67

Cluster analysis

The number of fixations was standardised (z-score) for cluster analysis to allow for different metrics in which the performance was measured. The number of clusters was initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final standardised number of fixations is two and participants in Cluster 2 (n=21) and tends to have a lower number of fixations than those in Cluster 1 (n = 10).

A Chi-square test for independence indicates no significant association between age and clustering outcome, χ^2 (1, n = 31) = 0.744, p = 0.386. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 0.744, p = 0.388. The association between wearing glasses and clustering outcome is also not significant, χ^2 (1, n = 31) = 3.004, p = 0.065.

Summary

The summary of statistical analysis of the number of fixation is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented.):

Young participants – step-heights (+125mm had more fixations than -60mm), direction (ascending step-heights had more fixations than descending step-heights);

Older participants – trial effect (Trial 1 had more fixations than Trial 2 and Trial 3);

Cluster analysis – none.

4.3.2 Mean fixation duration

Young participants

There is a non-significant main effect of step-height as well as lighting level on fixation duration (F (7, 702) = 1.046, p = 0.398, and F (1, 702) = 0.922, p = 0.337, respectively). The interaction effect between step-height and lighting level is not statistically significant (F (7, 702) = 1.794, p = 0.085). Direction has no statistical association with mean fixation duration with F (1, 702) = 0.208 and p = 0.648 (see Table 4-4).

Older participants

There is a non-significant main effect of step-height on mean fixation duration (F (7, 750) = 0.365, p = 0.923. There is a statistically significant main effect for lighting level, F (1, 750) = 4.419, p = 0.036; however the effect size (Partial Eta Squared = 0.09) is small. The mean fixation duration for 200lux (M = 161.81, SD = 105.60) is significantly shorter than that for 4lux (M = 176.58, SD = 93.80) at p = 0.036. The interaction effect between step-height and lighting level is not statistically significant (F (7, 750) = 0.559, p = 0.789). Direction has no significant association with mean fixation duration with F (1, 750) = 0.040 and p = 0.841 (see Table 4-4).

Table 4-4: Mean fixation duration (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.1808	0.1704	0.1567	0.1722	0.1733	0.1563	0.1834	0.1802
Old	0.1645	0.1667	0.1680	0.1748	0.1618	0.1647	0.1787	0.1744
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.1690	0.1656	0.1469	0.1499	0.1879	0.1581	0.2001	0.1680
Old	0.1685	0.1550	0.1523	0.1775	0.1566	0.1571	0.1645	0.1631
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.1926	0.1751	0.1666	0.1944	0.1587	0.1544	0.1667	0.1924
Old	0.1605	0.1784	0.1838	0.1720	0.1671	0.1722	0.1928	0.1858

Cluster analysis

The mean fixation duration was standardised (z-score) for cluster analysis to allow for different metrics in which the performance was measured. The number of clusters was initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final standardised number of clusters is two and participants in Cluster 2 (n = 15) tend to have a longer mean fixation duration than those in Cluster 1 (n = 16).

A Chi-square test for independence indicates no significant association between age and clustering outcome, χ^2 (1, n = 31) = 0.125, p = 0.723. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 0.125, p = 0.723. The association between glasses and clustering outcomes reaches statistical significance, χ^2 (1, n = 31) = 3.865, p = 0.044. Seven out of the 9 participants with glasses are clustered into Cluster 1 which has a shorter mean fixation duration.

Summary

The summary of statistical analysis of the mean fixation duration is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):
Young participants – none;
Older participants – lighting level (200lux had shorter mean fixation duration than 4lux);
Cluster analysis – glasses (those who wore glasses tended to have shorter mean fixation duration).

4.3.3 Total fixation time

Young participants

There is a statistically significant main effect for step-height, F (7, 702) = 2.768, p = 0.008, with the effect size (Partial Eta Squared) of 0.27. Post-hoc comparison test reveals that total fixation time for +125 mm (M = 631.39, SD = 167.48) is significantly greater than -60 mm (*M* = 337.66, *SD* = 141.99), -90 mm (*M* = 367.15, *SD* = 138.58) with *p* = 0.005 and 0.0024 respectively. The main effect for lighting level (*F* (1, 702) = 2.242, *p* = 0.135) does not reach statistical significance. The interaction effect between step-height and lighting level is not statistically significant (*F* (7, 702) = 1.520, *p* = 0.157). The sequence of trials accounts for variance in total fixation time with a statistically significant *F* (1, 702) = 3.079 at *p* =0.47 and effect size of 0.09. The post-hoc comparison tests reveals that total fixation time for Trial 1 (*M* = 531.02, *SD* = 171.31) is significantly longer than Trial 3 (*M* = 413.85, *SD* = 136.97) with *p* = 0.04. Direction is a significant factor with *F* (1, 702) = 12.339, *p* < 0.001 and effect size of 0.017. Ascending step-heights (*M* = 686.42, *SD* = 592.52) results in a longer total fixation time than descending step-heights (*M* = 546.27, *SD* = 480.28) at *p* < 0.001(see Table 4-5).

Older participants

There is a non-significant main effect of step-height as well as lighting level on total fixation time (*F* (7, 750) = 503, *p* = 0.832, and *F* (1, 750) = 0.304, *p* = 0.581, respectively). The interaction effect between step-height and lighting level is not statistically significant (*F* (7, 750) = 0.301, *p* = 0.954). The sequence of trials accounts for variance in total fixation time with a statistically significant *F* (1, 750) = 11.006 at *p* < 0.001 and effect size of 0.27. The post-hoc comparison tests reveal that the total fixation time for Trial 1 (*M* = 888.69, *SD* = 745.33) is significantly greater than Trial 2 (*M* = 710.49, *SD* = 601.44) and Trial 3 (*M* = 637.15, *SD* = 556.47) with *p* = 0.04 and *p* < 0.01 respectively. Direction has no significant association with total fixation time with *F* (1, 750) = 1.635 and *p* = 0.201 (see Table 4-5).

Table 4-5: Total fixation time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.5443	0.4240	0.3866	0.4916	0.5218	0.5296	0.6073	0.7087
Old	0.6774	0.6209	0.6358	0.6905	0.6172	0.5828	0.5710	0.6516
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.4319	0.3606	0.3461	0.4097	0.6304	0.5236	0.6537	0.5899
Old	0.7137	0.5956	0.5851	0.6857	0.5618	0.5884	0.5031	0.6203
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.6676	0.4903	0.4293	0.5789	0.4233	0.5354	0.5595	0.8379
Old	0.6421	0.6435	0.6846	0.6949	0.6750	0.5741	0.6428	0.6812

Cluster analysis

The total fixation time was standardised (z-score) for cluster analysis to allow for different metrics in which the performance was measured. The number of clusters was initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is four and participants in Cluster 3 tends to have the shortest total fixation time among all clusters (n = 7, 9, 12 and 2).

A Chi-square test for independence indicates no significant association between age and clustering outcome, χ^2 (1, n = 31) = 2.415, p = 0.364. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 3.577, *p* = 0.227. The association between glasses and clustering outcome reaches statistical significance, χ^2 (1, n = 31) = 10.170, *p* = 0.007. Seven out of the 9 participants with glasses are grouped into Cluster 3 which has a shorter total fixation time.

Summary

The summary of statistical analysis of the total fixation time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):

Young participants – step-height (+125mm had longer total fixation time than -60 and -90mm), trial effect (Trial 1 had longer total fixation time than Trial 3), direction (ascending step-heights had longer total fixation time than descending step-heights);

Older participants – trial effect (Trial 1 had longer total fixation time than Trial 2 and Trial 3);

Cluster analysis – glasses (those who wore glasses tended to have shorter total fixation time).

4.3.4 Total gaze time

Young participants

There is a non-significant main effect of step-height as well as lighting level on total gaze time (F (7, 557) = 1.200, p = 0.301, and F (1, 557) = 0.296, p = 0.587, respectively).

The interaction effect between step-height and lighting level is not statistically significant (F (7, 557) = 0.464, p = 0.860). The sequence of trials accounts for variance in total gaze time with a statistically significant F (1, 557) = 3.537 at p = 0.030 and effect size of 0.13. The post-hoc comparison test reveals that total gaze time for Trial 1 (M = 2.00, SD = 1.642) is significantly longer than Trial 2 (M = 1.592, SD = 1.487) at p = 0.028. Direction has no significant association with total gaze time with F (1, 702) = 3.289, p = 0.070 (see Table 4-6).

Older participants

There is a non-significant main effect of step-height on total gaze time (F (7, 609) = 1.689, p = 0.109. There is a statistically significant main effect for lighting level, F (1, 609) = 7.178, p = 0.008 with the effect size of 0.12. The total gaze time for 200lux (M = 2.117, SD = 1.777) is significantly longer than 4lux (M = 1.758, SD = 1.548) at p = 0.006. The interaction effect between step-height and lighting level is not statistically significant (F (7, 609) = 0.240, p = 0.975). The sequence of trials accounts for variance in total gaze time with a statistically significant F (1, 609) = 5.323 at p = 0.005 and effect size of 0.17. The post-hoc comparison test reveals that the total gaze time for Trial 1 (M = 2.117, SD = 1.777) is significantly longer than Trial 3 (M = 1.935, SD = 1.1.673) at p = 0.04. Direction has no significant association with total gaze time with F (1, 750) = 2.888 and p = 0.090 (see Table 4-6).

Table 4-6: Total gaze time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	1.5886	1.6579	1.5507	1.8477	1.8512	1.7265	1.8021	2.1858
Old	2.2992	1.9994	1.7802	2.1161	1.9691	2.0214	1.4931	1.8317
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	1.5272	1.6858	1.4553	1.7588	2.0097	1.4816	1.8848	2.1053
Old	2.3930	2.2370	2.0525	2.4054	2.0986	2.1039	1.5570	2.1207
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	1.6539	1.6328	1.6489	1.9340	1.6745	1.9434	1.7127	2.2579
Old	2.2030	1.7797	1.5328	1.8481	1.8428	1.9389	1.4276	1.5566

Cluster analysis

The total gaze time was standardised (z-score) for cluster analysis to allow for different metrics in which the performance was measured. The number of clusters was initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is two and participants in Cluster 2 (n = 23) tend to have a shorter total gaze time than those in Cluster 1 (n = 8).

A Chi-square test for independence indicates no significant association between age and clustering outcome, χ^2 (1, n = 31) = 0.011, p = 0.916. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 2.362, p = 0.117. The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 1.430, p = 0.206.

Summary

The summary of statistical analysis of the total gaze time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):
Younger participants – trial affect (Trial 1 had longer total gaze time than Trial 2);
Older participants – lighting level (200lux had longer total gaze time than 4lux), trial effect (Trial 1 had longer total gaze time than Trial 3);
Cluster analysis – none.

4.3.5 Early total gaze time

Young participants

There is a non-significant main effect of step-height as well as lighting on the early total gaze time (F (7, 557) = 0.666, p = 0.701, and F (1, 557) = 2.040, p = 0.154, respectively). The interaction effect between step-height and lighting level is not statistically significant (F (7, 557) = 0.277, p = 0.963). Direction has no significant association with the early total gaze time with F (1, 557) = 1.851 and p = 0.174 (see Table 4-7).

Older participants

There is a non-significant main effect of step-height on the early total gaze time (F (7, 609) = 1.095, p = 0.365. There is a statistically significant main effect for lighting level, F (1, 609) = 13.916, p < 0.001 with the effect size of 0.22. The total gaze time starts earlier at 200lux (M = 3.569, SD = 1.750) than 4lux (M = 3.065, SD = 1.577) at p < 0.001. The interaction effect between step-height and lighting level is not statistically significant (F (7, 609) = 0.399, p = 0.903). The sequence of trials accounts for variance in the early total gaze time with a statistically significant F (1, 609) = 5.250 at p = 0.005 and effect size of 0.17. The post-hoc comparison test reveals that the total gaze time started significantly earlier in Trial 1 (M = 3.587, SD = 1.880) than Trial 3 (M = 3.066, SD = 1.595) at p = 0.04. Direction has no significant association with the early total gaze time with F (1, 609) = 1.656 and p = 0.199 (see Table 4-7).

Table 4-7: Early total gaze time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	4.0140	4.4704	3.9906	4.1153	4.4032	4.3037	4.3800	4.3789
Old	3.5599	3.2650	3.3661	3.3890	3.2344	3.5529	2.9560	3.2032
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	4.1188	4.3909	3.8632	3.9821	4.3420	3.9417	4.2456	4.1878
Old	3.6344	3.6410	3.7486	3.7414	3.5609	3.7689	3.0523	3.4410
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	3.9065	4.5431	4.1216	4.2447	4.4714	4.6242	4.5252	4.5498
Old	3.4834	2.9172	3.0181	3.0624	2.9162	3.3368	2.8572	2.9766

Cluster analysis

The early total gaze time was standardised (z-score) for cluster analysis to allow for different metrics in which the performance was measured. The number of clusters was initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final standardised number of clusters is four and participants in Cluster 3 tend to start the total gaze time earlier than rest of the clusters (n=5, 4, 10 and 12).

A Chi-square test for independence indicates no significant association between age and clustering outcome, χ^2 (1, n = 31) = 4.506, p = 0.195. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 4.773, p = 0.175. The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 5.034, p = 0.102.

Summary

The summary of statistical analysis of the early total gaze time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):
Younger participants – trial affect (Trial 1 had earlier early total gaze time than Trial 2);
Older participants – lighting level (200lux had earlier early total gaze time than 4lux), trial effect (Trial 1 had earlier early total gaze time than Trial 3);
Cluster analysis – none.

4.3.6 Late total gaze time

Young participants

There is a non-significant main effect of step-height as well as lighting level on the late total gaze time (F (7, 557) = 0.988, p = 0.439, and F (1, 557) = 1.405, p = 0.236, respectively). The interaction effect between step-height and lighting level is not statistically significant (F (7, 557) = 0.419, p = 0.891). Direction has no significant association with the late total gaze time with F (1, 557) = 0.005 and p = 0.942 (see Table 4-8).

Older participants

There is a non-significant main effect of step-height as well as lighting level on the late total gaze time (F (7, 609) = 1.260, p = 0.268, and F (1, 609) = 3.104, p = 0.079, respectively). The interaction effect between step-height and lighting level is not statistically significant (F (7, 609) = 0.493, p = 0.840). Direction has no significant association with the late total gaze time with *F* (1, 609) = 0.380 and *p* = 0.538 (see Table 4-8).

Table 4-8: Late total gaze time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	2.4254	2.8124	2.4401	2.2681	2.5521	2.5771	2.5786	2.1937
Old	1.2607	1.2656	1.5858	1.2729	1.2653	1.5315	1.4629	1.3714
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	2.5930	2.7056	2.4088	2.2236	2.3326	2.4599	2.3612	2.0835
Old	1.2415	1.4040	1.6964	1.3360	1.4623	1.6651	1.4953	1.3204
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	2.2534	2.9104	2.4724	2.3113	2.7968	2.6810	2.8136	2.2922
Old	1.2804	1.1375	1.4853	1.2143	1.0734	1.3979	1.4296	1.4200

Cluster analysis

The late total gaze time was standardised (z-score) for cluster analysis to allow for different metrics in which the performance was measured. The number of clusters was initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is four and participants in Cluster 1 tend to finish total gaze time the earliest whereas those in Cluster 4 tend to finish total gaze time the latest among all clusters (n = 4, 10, 5 and 12).

A Chi-square test for independence indicates a significant association between age and clustering outcome, χ^2 (1, n = 31) = 9.911, p = 0.008. Young participants are clustered into all four clusters with the fewest in the fourth cluster (n = 4, 6, 3 and 2) whereas more than 10 out of 16 older participants (n = 0, 4, 2 and 10) are clustered into the fourth cluster, which reveals that older participants tend to finish total fixation time later than young participants. There is not any significant association between gender and clustering outcome, χ^2 (1, n = 31) = 1.569, *p* = 0.655. The association between glasses and clustering outcome is noticeable thought not statistically significant, χ^2 (1, n = 31) = 5.195, *p* = 0.055. Because of the small sample size as a whole as well as for each subgroup (with or without glasses), the noticeable association is still worth reporting. More than half of the participants with glasses are clustered into the fourth cluster (n = 0, 4, 0 and 5) as opposed to those without glasses (n = 4, 6, 5 and 7), which reveals that participants with glasses tend to finish total gaze time later than those without glasses. Among the five participants with glasses in the fourth cluster, four of them are older participants.

Summary

The summary of statistical analysis of the late total gaze time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):
Younger participants – none;
Older participants – none;
Cluster analysis – age (older participants tended to finish total gaze time later), glasses (those who wore glasses tended to finish total gaze time later).

4.4 Gait pattern (physical capability)

The analysis of the four gait variables (double support time (section 5.4.1), stride time (section 5.4.2), stance time (section 5.4.3) and swing time (section 5.4.4)) will be elaborated in the following subsections. The mean value, standard deviation and coefficient of variation for each variable will constitute the analysis in each subsection.

4.4.1 Double support time

4.4.1.1 Mean double support time

Young participants

There is a non-significant main effect of step-height on mean double support time (F (7, 700) = 0.483, p = 0.847. There is a statistically significant main effect for lighting level, F (1, 700) = 7.397, p = 0.007 with the effect size of 0.10. The mean double support time for 200lux (M = 0.1628, SD = 0.0378) is significantly shorter than 4lux (M = 0.1699, SD = 0.0317) at p = 0.007. The interaction effect between step-height and lighting level is not statistically significant (F (7, 700) = 1.060, p = 0.388). Direction has no significant association with the mean double support time with *F* (1, 700) = 1.217 and *p* = 0.270 (see Table 4-9).

Older participants

There is a non-significant main effect of step-height on mean double support time (*F* (7, 744) = 1.358, *p* = 0.220. There is a statistically significant main effect for lighting level, *F* (1, 744) = 4.937, *p* < 0.001 with the effect size of 0.29. The mean double support time for 200lux (*M* = 0.1541, *SD* = 0.0328) is significantly shorter than 4lux (*M* = 0.1657, *SD* = 0.0349) at *p* = 0.001. The interaction effect between step-height and lighting level is not statistically significant (*F* (7, 744) = 0.458, *p* = 0.865). Direction has no significant association with the mean double support time with *F* (1, 744) = 3.325 and *p* = 0.069 (see Table 4-9).

Table 4-9: Mean double support time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.1648	0.1624	0.1661	0.1663	0.1669	0.1716	0.1666	0.1660
Old	0.1556	0.1557	0.1573	0.1617	0.1583	0.1675	0.1596	0.1632
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.1598	0.1556	0.1590	0.1635	0.1594	0.1748	0.1648	0.1654
Old	0.1486	0.1477	0.1508	0.1562	0.1511	0.1671	0.1536	0.1579
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.1698	0.1692	0.1733	0.1691	0.1744	0.1683	0.1684	0.1665
Old	0.1627	0.1642	0.1637	0.1673	0.1656	0.1680	0.1656	0.1684

Cluster analysis

The mean double support time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance was measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is four and participants in Cluster 2 tend to have the longest mean double support time and those in Cluster 1 tend to be the shortest among all clusters (n = 8, 6, 9 and 8).

A Chi-square test for independence indicates significant association between age and clustering outcome, χ^2 (1, n = 31) = 1.970, *p* = 0.573. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 0.579, *p* = 0.900.

The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 0.598, p = 0.897.

Summary

The summary of statistical analysis of the mean double support time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):

Young participants – lighting level (200lux had longer mean double support time than 4lux);

Older participants – lighting level (200lux had longer mean double support time than 4lux)

Cluster analysis – none.

4.4.1.2 Standard deviation of double support time

Young participants

There is a non-significant main effect of step-height on standard deviation of double support time (F (7, 700) = 1.955, p = 0.59. There is a statistically significant main effect for lighting level, F (1, 700) = 12.571, p < 0.001 with the effect size of 0.18. The standard deviation of double support time for 200lux (M = 0.0142, SD = 0.0040) is significantly lower than 4lux (M = 0.0154, SD = 0.0050) at p < 0.001. The interaction effect between step-height and lighting level is not statistically significant (F (7, 700) = 0.848, p = 0.547). Direction is a significant factor with F (1, 700) = 7.014, p = 0.008 and effect size of 0.010. Ascending step-heights (M = 0.0152, SD = 0.0048) has greater standard deviation than descending step-heights (M = 0.0143, SD = 0.0043) at p < 0.001 (see Table 4-10).

Older participants

There is a non-significant main effect of step-height as well as lighting level on standard deviation of double support time(F (7, 744) = 1.369, p = 0.215, and F (1, 744) = 1.426, p = 0.233, respectively). The interaction effect between step-height and lighting level is not statistically significant (F (7, 744) = 0.785, p = 0.600). Direction has no significant association with the standard deviation of double support time with F (1, 744) = 1.786 and p = 0.182 (see Table 4-10).

Table 4-10: Standard deviation of double support time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0150	0.0140	0.0137	0.0146	0.0147	0.0155	0.0152	0.0154
Old	0.0162	0.0151	0.0155	0.0164	0.0153	0.0145	0.0150	0.0162
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0140	0.0135	0.0129	0.0140	0.0146	0.0145	0.0142	0.0155
Old	0.0158	0.0156	0.0149	0.0161	0.0142	0.0141	0.0153	0.0163
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0160	0.0144	0.0145	0.0151	0.0147	0.0166	0.0162	0.0154
Old	0.0166	0.0146	0.0161	0.0167	0.0164	0.0149	0.0147	0.0161

Cluster analysis

The standard deviation of double support time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is two and participants in Cluster 2 (n = 5) tend to have a greater standard deviation of double support time than those in Cluster 1 (n = 26).

A Chi-square test for independence indicates no significant association between age and clustering outcome, χ^2 (1, n = 31) = 1.924, p = 0.152. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 0.322, p = 0.570. The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 0.348, p = 0.565.

Summary

The summary of statistical analysis of the standard deviation of double support time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):

Young participants – lighting level (4lux had greater standard deviation of double support time than 200lux), direction (ascending step-heights had greater standard deviation of double support time than descending step-heights);

Older participants – none;

Cluster analysis – none.

4.4.1.3 Coefficient of variation of double support time

Young participants

There is a non-significant main effect of step-height as well as lighting level on coefficient of variation of double support time (F (7, 700) = 1.335, p = 0.231, and F (1, 700) = 1.098, p = 0.295, respectively). The interaction effect between step-height and lighting level is not statistically significant (F (7, 700) = 1.109, p = 0.355). Direction has no significant association with the coefficient of variation of double support time with F (1, 700) = 3.722 and p = 0.054 (see Table 4-11).

Older participants

There is a non-significant main effect of step-height as well as lighting level on coefficient of variation of double support time(F (7, 744) = 1.588, p = 0.136, and F (1, 744) = 1.433, p = 0.232, respectively). The interaction effect between step-height and lighting level is not statistically significant (F (7, 744) = 0.812, p = 0.577). Direction is a significant factor with F (1, 744) = 3.850, p = 0.05 and effect size of 0.005. Descending step-heights (M = 0.1035, SD = 0.0445) has greater coefficient of variation than ascending step-heights (M = 0.0976, SD = 0.0380) at p = 0.05 (see Table 4-11).

Table 4-11: Coefficient of variation of double support time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0946	0.0890	0.0847	0.0908	0.0917	0.0941	0.0950	0.0972
Old	0.1085	0.1017	0.1020	0.1020	0.1012	0.0898	0.0969	0.1025
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0919	0.0903	0.0838	0.0890	0.0962	0.0870	0.0906	0.0985
Old	0.1082	0.1109	0.1021	0.1021	0.0995	0.0881	0.1012	0.1064
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0974	0.0878	0.0857	0.0927	0.0873	0.1014	0.0993	0.0960
Old	0.1087	0.0918	0.1018	0.1018	0.1028	0.0915	0.0927	0.0987

Cluster analysis

The coefficient of variation of double support time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of cluster is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is two and participants in Cluster 1 (n = 8) tend to have a greater coefficient of variation of double support time than those in Cluster 2 (n = 23).

A Chi-square test for independence indicates significant association between age and clustering outcome, χ^2 (1, n = 31) = 2.362, p = 0.117. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 0.011, p = 0.916. The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 0.375, p = 0.546.

Summary

The summary of statistical analysis of the coefficient of variation of double support time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):
Young participants – none;
Older participants – direction (descending step-heights had greater coefficient of variation than ascending step-heights);
Cluster analysis – none.

4.4.2 Stride time

4.4.2.1 Mean stride time

Young participants

There is a non-significant main effect of step-height on mean stride time (F (7, 700) = 0.149, p = 0.994. There is a statistically significant main effect for lighting level, F (1, 700) = 6.357, p = 0.012, with the effect size of 0.09. The mean stride time for 200lux (M = 1.0440, SD = 0.0651) is significantly shorter than 4lux (M = 1.0565, SD = 0.0658) at p =

0.012. The interaction effect between step-height and lighting level is not statistically significant (F (7, 700) = 0.080, p = 0.999). Direction has no significant association with mean stride time with F (1, 700) = 0.204 and p = 0.652 (see Table 4-12).

Older participants

There is a non-significant main effect of step-height on mean stride time (F (7, 744) = 0.321, p = 0.945. There is a statistically significant main effect for lighting level, F (1, 744) = 4.816, p = 0.028, with the effect size of 0.06. The mean stride time for 200lux (M = 1.0457, SD = 0.0654) is significantly shorter than 4lux (M = 1.057, SD = 0.0715) at p = 0.028. The interaction effect between step-height and lighting level is not statistically significant (F (7, 744) = 0.428, p = 0.885). Direction has no significant association with mean stride time with F (1, 744) = 0.042 and p = 0.838 (see Table 4-12).

Table 4-12: Mean stride time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	1.0548	1.0535	1.0507	1.0464	1.0497	1.0492	1.0484	1.0493
Old	1.0502	1.0502	1.0503	1.0556	1.0474	1.0587	1.0473	1.0494
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	1.0488	1.0482	1.0469	1.0387	1.0430	1.0459	1.0401	1.0407
Old	1.0431	1.0425	1.0419	1.0480	1.0380	1.0628	1.0407	1.0485
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	1.0607	1.0589	1.0545	1.0544	1.0564	1.0526	1.0566	1.0579
Old	1.0575	1.0584	1.0586	1.0633	1.0568	1.0547	1.0539	1.0503

Cluster analysis

The mean stride time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is four and participants in Cluster 3 tend to have the longest mean stride time and those in Cluster 1 tend to have the shortest mean stride time among all clusters (n = 7, 7, 6, 11).

A Chi-square test for independence indicates significant association between age and clustering outcome, χ^2 (1, n = 31) = 1.012, p = 0.795. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 4.886, p = 0.159.

The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 1.112, p = 0.773.

Summary

The summary of statistical analysis of the mean stride time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):
Young participants – lighting level (4lux had longer mean stride time than 200lux);
Older participants – lighting level (4lux had longer mean stride time than 200lux);
Cluster analysis – none.

4.4.2.2 Standard deviation of stride time

Young participants

There is a statistically significant main effect for step-height, F (7, 700) = 11.671, p < 0.001, with the effect size (Partial Eta Squared) of 0.105. Post-hoc comparison tests reveal that standard deviation of stride time for -125 mm (M = 0.0305, SD = 0.0172) is significantly greater than -60 mm (M = 0.0217, SD = 0.0111), -30 mm (M = 0.0217, SD = 0.0100), +30 mm (M = 0.0180, SD = 0.0069), +60 mm (M = 0.0206, SD = 0.0816), +90 mm (M = 0.0189, SD = 0.0085) and +125 mm (M = 0.0213, SD = 0.0101) with all p < 0.001. Standard deviation for -90 mm (M = 0.0189, SD = 0.0085) is also significantly greater than +30 mm (M = 0.0180, SD = 0.0069) with p < 0.001. The main effect for lighting level (F (1, 700) = 1.796, p = 0.181) does not reach statistical significance. The interaction effect between step-height and lighting level is not statistically significant (F (7, 700) = 1.1843, p = 0.076). Direction is a significant factor with F (1, 700) = 36.214, p < 0.001 and effect size of 0.048. Descending step-heights (M = 0.0248, SD = 0.0136) has greater standard deviation than ascending step-heights (M = 0.0197, SD = 0.0085) at p < 0.001 (see Table 4-13).

Older participants

There is a statistically significant main effect for step-height, F (7, 744) = 6.714, $p <$ 0.001, with the effect size (Partial Eta Squared) of 0.59. Post-hoc comparison tests reveal that standard deviation of stride time for -125 mm (M = 0.0373, SD = 0.0229) is significantly greater than +30 mm (M = 0.0261, SD = 0.0145), +60 mm (M = 0.0253, SD = 0.0120), +90 mm (M = 0.0258, SD = 0.0132) and +125 mm (M = 0.0266, SD = 0.0132) with all p < 0.001. The main effect for lighting level (F (1, 744) = 1.651, p = 0.199) does not reach statistical significance. The interaction effect between step-height and lighting level is not statistically significant (F (7, 744) = 0.726, p = 0.620). Direction is a significant factor with F (1, 744) = 38.159, p < 0.001 and effect size of 0.048. Descending step-heights (M = 0.0336, SD = 0.0202) has greater standard deviation than ascending step-heights (M = 0.0260, SD = 0.0132) at p < 0.001 (see Table 4-13).

Table 4-13: Standard deviation of stride time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0305	0.0252	0.0217	0.0217	0.0180	0.0206	0.0189	0.0213
Old	0.0373	0.0340	0.0330	0.0301	0.0261	0.0253	0.0258	0.0266
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0284	0.0223	0.0206	0.0236	0.0172	0.0200	0.0201	0.0212
Old	0.0343	0.0332	0.0333	0.0277	0.0251	0.0268	0.0262	0.0253
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0325	0.0281	0.0228	0.0198	0.0187	0.0211	0.0177	0.0215
Old	0.0402	0.0350	0.0327	0.0326	0.0272	0.0239	0.0254	0.0277

Cluster analysis

The standard deviation of stride time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is four and participants in Cluster 4 tend to have the smallest standard deviation among all clusters (n = 1, 1, 2, 27).

A Chi-square test for independence indicates significant association between age and clustering outcome, χ^2 (1, n = 31) = 2.007, p = 0.427. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 2.007, p = 0.427. The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 5.923, p = 0.113.

Summary

The summary of statistical analysis of the standard deviation of stride time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):

Young participants – step-heights (-125mm had greater standard deviation of stride time than -30, +30, +60, +90 and +125 mm; -90mm had greater standard deviation of stride time than +30 mm), direction (descending step-heights had greater standard deviation of stride time than ascending step-heights);

Older participants – step-heights (-125mm had greater standard deviation of stride time than +30, +60, +90 and +125mm), direction (descending step-heights had greater standard deviation of stride time than ascending step-heights);

Cluster analysis – none.

4.4.2.3 Coefficient of variation of stride time

Young participants

There is a statistically significant main effect for step-height, F (7, 700) = 11.416, $p <$ 0.001, with the effect size (Partial Eta Squared) of 0.102. Post-hoc comparison tests reveal that coefficient of variation of stride time for -125 mm (M = 0.0288, SD = 0.0161) is significantly greater than -60 mm (M = 0.0206, SD = 0.0105), -30 mm (M = 0.0208, SD = 0.0093), +30 mm (M = 0.0171, SD = 0.0063), +60 mm (M = 0.0197, SD = 0.0079), +90 mm (M = 0.0180, SD = 0.0080) and +125 mm (M = 0.0204, SD = 0.0097) with all $p <$ 0.001. Coefficient of variation for -90 mm (M = 0.0239, SD = 0.0124) is also significantly greater than +30 mm (M = 0.0171, SD = 0.0063) with $p < 0.001$. The main effect for lighting level (F (1, 700) = 1.072, p = 0.301) does not reach statistical significance. The interaction effect between step-height and lighting level is not statistically significant (F (7, 700) = 1.933, p = 0.062). Direction is a significant factor with F (1, 700) = 35.534, p

< 0.001 and effect size of 0.048. Descending step-heights (*M* = 0.0235, *SD* = 0.0127) has greater coefficient of variation than ascending step-heights (*M* = 0.0188, *SD* = 0.0081) at $p < 0.001$(see Table 4-14).

Older participants

There is a statistically significant main effect for step-height, F (7, 744) = 7.573, $p <$ 0.001, with the effect size (Partial Eta Squared) of 0.67. Post-hoc comparison tests reveal that coefficient of variation of stride time for -125 mm (*M* = 0.0356, *SD* = 0.0196) is significantly greater than +30 mm (*M* = 0.0247, *SD* = 0.0129), +60 mm (*M* = 0.0239, *SD* = 0.0110), +90 mm (*M* = 0.0245, *SD* = 0.0123) and +125 mm (*M* = 0.0252, *SD* = 0.0122) with all $p < 0.001$. The main effect for lighting level (F (1, 744) = 0.789, p = 0.375) does not reach statistical significance. The interaction effect between step-height and lighting level is not statistically significant (F (7, 744) = 0.624, p = 0.737). Direction is a significant factor with F (1, 744) = 42.192, $p < 0.001$ and effect size of 0.053. Descending step-heights (*M* = 0.0318, *SD* = 0.0181) has greater coefficient of variation than ascending step-heights (*M* = 0.0246, *SD* = 0.0121) at $p < 0.001$ (see Table 4-14).

Table 4-14: Coefficient of variation of stride time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0288	0.0239	0.0206	0.0208	0.0171	0.0197	0.0180	0.0204
Old	0.0355	0.0322	0.0311	0.0285	0.0247	0.0239	0.0245	0.0252
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0271	0.0212	0.0197	0.0227	0.0165	0.0192	0.0194	0.0203
Old	0.0337	0.0317	0.0317	0.0264	0.0241	0.0253	0.0250	0.0239
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0305	0.0267	0.0216	0.0188	0.0177	0.0201	0.0167	0.0204
Old	0.0374	0.0327	0.0306	0.0305	0.0254	0.0225	0.0240	0.0265

Cluster analysis

The coefficient of variation of stride time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is four and participants in Cluster 1 tend to have the smallest coefficient of variation among all clusters (n = 26, 1, 3, 1).

A Chi-square test for independence indicates significant association between age and clustering outcome, χ^2 (1, n = 31) = 2.457, p = 0.357. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 2.437, p = 0.357. The association between glasses and clustering outcome reached statistical significance, χ^2 (1, n = 31) = 8.163, p = 0.044. Participants with glasses are clustered into all four of the clusters (n = 5, 1, 2, 1) whereas almost all of those without glasses are clustered into the first cluster (n = 21, 0, 1, 0), indicating that participants without glasses tend to have smaller coefficient of variation of stride time.

Summary

The summary of statistical analysis of the coefficient of variation of stride time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):
Younger participants – step-heights (-125mm had greater coefficient of variation of stride time than -60, -30, +30, +60, +90 and +125mm; -90 had greater coefficient of variation of stride time than +30 mm), direction (descending step-heights had greater coefficient of variation of stride time than ascending step-heights);
Older participants - step-heights (-125mm had greater coefficient of variation of stride time than +30, +60, +90 and +125mm), direction (descending step-heights had greater coefficient of variation than ascending step-heights);
Cluster analysis – glasses (those who wore glasses tended to have smaller coefficient of variation of stride time).

4.4.3 Stance time

4.4.3.1 Mean stance time

Young participants

There is a non-significant main effect of step-height on mean stance time (F (7, 700) = 0.066, p = 1.000. There is a statistically significant main effect for lighting level, F (1,

700) = 9.599, p = 0.002 with effect size (Partial Eta Squared) of 0.14. The mean stance time for 200lux (M = 0.6036, SD = 0.0463) is significantly shorter than 4lux (M = 0.6143, SD = 0.0451) at p = 0.002. The interaction effect between step-height and lighting level is not statistically significant (F (7, 700) = 0.149, p = 0.994. Direction has no significant association with stance time with F (1, 700) = 0.032 and p = 0.859 (see Table 4-15).

Older participants

There is a non-significant main effect of step-height on mean stance time (F (7, 744) = 0.676, p = 0.692. There is a statistically significant main effect for lighting level, F (1, 744) = 12.660, p < 0.001, with effect size (Partial Eta Squared) of 0.017. The mean stance time for 200lux (M = 0.5999, SD = 0.0395) is significantly shorter than 4lux (M = 0.6112, SD = 0.0471) at p < 0.001. The interaction effect between step-height and lighting level is not statistically significant (F (7, 744) = 0.581, p = 0.772). Direction has no significant association with mean stance time with F (1, 744) = 0.299 and p = 0.585 (see Table 4-15).

Table 4-15: Mean stance time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.6692	0.6672	0.6667	0.6653	0.6682	0.6691	0.6674	0.6672
Old	0.6029	0.6030	0.6038	0.6087	0.6028	0.6131	0.6035	0.6063
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.6648	0.6618	0.6624	0.6586	0.6622	0.6678	0.6622	0.6616
Old	0.5959	0.5951	0.5964	0.6021	0.5945	0.6149	0.5972	0.6032
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.6735	0.6725	0.6711	0.6722	0.6742	0.6704	0.6725	0.6727
Old	0.6101	0.6113	0.6112	0.6153	0.6112	0.6113	0.6097	0.6093

Cluster analysis

The mean stance time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is two and participants in Cluster 1 (n = 18) tend to have shorter mean stance time than those in Cluster 2 (n = 13).

A Chi-square test for independence indicates significant association between age and clustering outcome, χ^2 (1, n = 31) = 0.988, p = 0.802. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 4.048, p = 0.245. The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 1.278, p = 0.746.

Summary

The summary of statistical analysis of the mean stance time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):
Young participants – lighting level (4lux had longer mean stance time than 200lux);
Older participants – lighting level (4lux had longer mean stance time than 200lux);
Cluster analysis – none.

4.4.3.2 Standard deviation of stance time

Young participants

There is a statistically significant main effect for step-height, F (7, 700) = 6.467, p < 0.001, with the effect size (Partial Eta Squared) of 0.61. Post-hoc comparison tests reveal that standard deviation of stance time for -125 mm (M = 0.0157, SD = 0.0074) is significantly greater than -90 mm (M = 0.0140, SD = 0.0064), -60 mm (M = 0.0127, SD = 0.0057), -30 mm (M = 0.0122, SD = 0.0045), +30 mm (M = 0.0106, SD = 0.0044), +60 mm (M = 0.0125, SD = 0.0049), +90 mm (M = 0.0116, SD = 0.0049) and +125 mm (M = 0.0124, SD = 0.0061) with p = 009, p =0,001, p < 0.01, p =0.005, p < 0.001 and p = 0.002 respectively. Standard deviation for -90 mm (M = 0.0116, SD = 0.0049) is also significantly greater than +30 mm (M = 0.0106, SD = 0.0044) with p = 0.03. The main effect for lighting level (F (1, 700) = 1.377, p = 0.241) does not reach statistical significance. The interaction effect between step-height and lighting level is not statistically significant (F (7, 700) = 0.738, p = 0.640). Direction is a significant factor with F (1, 700) = 18.099, p < 0.001 and effect size of 0.025. Descending step-heights (M

= 0.0136, *SD* = 0.0062) has greater standard deviation than ascending step-heights (*M* = 0.0118, *SD* = 0.0052) at $p < 0.001$ (see Table 4-16).

Older participants

There is a statistically significant main effect for step-height, F (7, 744) = 3.064, p = 0.003, with the effect size (Partial Eta Squared) of 0.28. Post-hoc comparison tests reveal that standard deviation of stance time for -125 mm (*M* = 0.0195, *SD* = 0.0118) is significantly greater than +60 mm (*M* = 0.0149, *SD* = 0.0071) with p = 0.034. The main effect for lighting level (F (1, 744) = 0.367, p = 0.693) does not reach statistical significance. The interaction effect between step-height and lighting level is not statistically significant (F (7, 744) = 0.769, p = 0.614). Direction is a significant factor with F (1, 744) = 19.971, $p < 0.001$ and effect size of 0.026. Descending step-heights (*M* = 0.0186, *SD* = 0.0110) has greater standard deviation than ascending step-heights (*M* = 0.0154, *SD* = 0.0085) at $p < 0.001$ (see Table 4-16).

Table 4-16: Standard deviation of stance time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0157	0.0139	0.0127	0.0122	0.0107	0.0125	0.0116	0.0124
Old	0.0195	0.0180	0.0187	0.0183	0.0155	0.0149	0.0155	0.0158
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0154	0.0127	0.0125	0.0126	0.0103	0.0121	0.0117	0.0125
Old	0.0179	0.0174	0.0193	0.0172	0.0142	0.0157	0.0158	0.0154
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0160	0.0152	0.0129	0.0117	0.0110	0.0130	0.0116	0.0123
Old	0.0211	0.0185	0.0181	0.0193	0.0168	0.0142	0.0152	0.0161

Cluster analysis

The standard deviation of stance time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is three and participants in Cluster 1 tend to have the smallest standard deviation among all clusters (n = 26, 1, 4).

A Chi-square test for independence indicates significant association between age and clustering outcome, χ^2 (1, n = 31) = 2.124, p = 0.279. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 0.969, p = 0.508. The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 3.746, p = 0.156.

Summary

The summary of statistical analysis of the standard deviation of stance time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):
Younger participants – step-heights (-125mm had greater standard deviation of stance time than all the others step-heights; -90mm had greater standard deviation of stance time than 30mm), direction (descending step-heights had greater standard deviation of stance time than ascending step-heights);
Older participants – step-heights (-125 had greater standard deviation of stance time than 60mm), direction (descending step-heights had greater standard deviation of stance time than ascending step-heights);
Cluster analysis – none.

4.4.3.3 Coefficient of variation of stance time

Young participants

There is a statistically significant main effect for step-height, F (7, 700) = 6.469, p < 0.001, with the effect size (Partial Eta Squared) of 0.061. Post-hoc comparison tests reveal that coefficient of variation of stance time for -125 mm (M = 0.0259, SD = 0.0123) is significantly greater than -90 mm (M = 0.0228, SD = 0.0104), -60 mm (M = 0.0207, SD = 0.0093), -30 mm (M = 0.0201, SD = 0.0073), +30 mm (M = 0.0175, SD = 0.0072), +60 mm (M = 0.0207, SD = 0.0084), +90 mm (M = 0.0191, SD = 0.0080) and +125 mm (M = 0.0204, SD = 0.0103) with p = 006, p =0,001, p < 0.01, p =0.005, p < 0.001 and p = 0.002 respectively. Coefficient of variation for -90 mm (M = 0.0228, SD = 0.0104) was also significantly greater than +30 mm (M = 0.0175, SD = 0.0072) with p =

0.04. The main effect for lighting level (*F* (1, 700) = 0.354, *p* = 0.552) does not reach statistical significance. The interaction effect between step-height and lighting level is not statistically significant (*F* (7, 700) = 0.739, *p* = 0.639). Direction is a significant factor with *F* (1, 700) = 17.708, *p* < 0.001 and effect size of 0.024. Descending step-heights (*M* = 0.0224, *SD* = 0.0102) has greater coefficient of variation than ascending step-heights (*M* = 0.0194, *SD* = 0.0086) at *p* < 0.001 (see Table 4-17).

Older participants

There is a statistically significant main effect for step-height, *F* (7, 744) = 3.334, *p* = 0.002, with the effect size (Partial Eta Squared) of 0.30. Post-hoc comparison tests reveal that coefficient of variation of stance time for -125 mm (*M* = 0.0316, *SD* = 0.0173) is significantly greater than +60 mm (*M* = 0.0243, *SD* = 0.0114) with *p* = 0.034. The main effect for lighting level (*F* (1, 744) = 0.290, *p* = 0.590) does not reach statistical significance. The interaction effect between step-height and lighting level is not statistically significant (*F* (7, 744) = 0.681, *p* = 0.688). Direction is a significant factor with *F* (1, 744) = 21.760, *p* < 0.001 and effect size of 0.028. Descending step-heights (*M* = 0.0304, *SD* = 0.0169) has greater coefficient of variation than ascending step-heights (*M* = 0.0252, *SD* = 0.0133) at *p* < 0.001 (see Table 4-17).

Table 4-17: Coefficient of variation of stance time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0288	0.0239	0.0206	0.0208	0.0171	0.0197	0.0180	0.0204
Old	0.0316	0.0293	0.0307	0.0298	0.0253	0.0243	0.0255	0.0259
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0271	0.0212	0.0197	0.0227	0.0165	0.0192	0.0194	0.0203
Old	0.0297	0.0290	0.0321	0.0286	0.0237	0.0255	0.0262	0.0253
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0305	0.0267	0.0216	0.0188	0.0177	0.0201	0.0167	0.0204
Old	0.0336	0.0297	0.0293	0.0311	0.0268	0.0231	0.0248	0.0264

Cluster analysis

The coefficient of variation of stance time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is two and participants in Cluster 1 (n = 29) tend to have smaller coefficient of variation than those in Cluster 2 (n = 2).

A Chi-square test for independence indicates significant association between age and clustering outcome, χ^2 (1, n = 31) = 2.004, p = 0.096. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 2.004, p = 0.096. The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 5.226, p = 0.21. It is worth to note that the two participants in Cluster 2 are both female elderly with glasses.

Summary

The summary of statistical analysis of the coefficient of variation of stance time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):
Younger participants – step-heights (-125 had greater coefficient of variation of stance time than all the others step-heights; -90mm had greater coefficient of variation of stance time than +30mm), direction (descending step-heights had greater coefficient of variation than ascending step-heights);
Older participants – step-heights (-125 had greater coefficient of variation of stance time +60mm), direction (descending step-heights had greater coefficient of variation than ascending step-heights);
Cluster analysis – none.

4.4.4 Swing time

4.4.4.1 Mean swing time

Young participants

There is a non-significant main effect of step-height as well as lighting level on mean swing time (F (7, 700) = 0.671, p = 0.697, and F (1, 700) = 3.552, p = 0.060, respectively). The interaction effect between step-height and lighting level is not statistically significant (F (7, 700) = 0.634, p = 0.728). Direction has no significant association with mean swing time with F (1, 700) = 1.422 and p = 0.234 (see Table 4-18).

Older participants

There is a non-significant main effect of step-height as well as lighting level on mean swing time (F (7, 744) = 0.243, p = 0.974, and F (1, 744) = 0.015, p = 0.902, respectively). The interaction effect between step-height and lighting level is not statistically significant (F (7, 744) = 0.167, p = 0.992). Direction has no significant association with mean swing time with F (1, 744) = 1.390 and p = 0.239 (see Table 4-18).

Table 4-18: Mean swing time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.4454	0.4461	0.4427	0.4405	0.4420	0.4391	0.4416	0.4425
Old	0.4473	0.4473	0.4465	0.4470	0.4445	0.4456	0.4439	0.4431
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.4445	0.4463	0.4439	0.4376	0.4418	0.4355	0.4377	0.4377
Old	0.4472	0.4474	0.4456	0.4459	0.4434	0.4479	0.4436	0.4453
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.4462	0.4459	0.4414	0.4436	0.4422	0.4428	0.4455	0.4473
Old	0.4474	0.4471	0.4475	0.4480	0.4456	0.4433	0.4442	0.4410

Cluster analysis

The mean swing time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is two and participants in Cluster 1 (n = 17) tend to have shorter mean swing time than those in Cluster 2 (n = 14).

A Chi-square test for independence indicates significant association between age and clustering outcome, χ^2 (1, n = 31) = 1.393, p = 0.645. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 0.027, p = 0.870. The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 2.584, p = 0.106.

Summary

The summary of statistical analysis of the mean swing time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):
Young participants – none;
Older participants – none;
Cluster analysis – none.

4.4.4.2 Standard deviation of swing time

Young participants

There is a statistically significant main effect for step-height, F (7, 700) = 6.960, p <0.001, with the effect size (Partial Eta Squared) of 0.65. Post-hoc comparison tests reveal that standard deviation of swing time for -125 mm (M = 0.0177, SD = 0.0093) is significantly greater than -60 mm (M = 0.0136, SD = 0.0060), -30 mm (M = 0.0138, SD = 0.0056), +30 mm (M = 0.0127, SD = 0.0032), +60 mm (M = 0.0132, SD = 0.0043), +90 mm (M = 0.0130, SD = 0.0049) and +125 mm (M = 0.0139, SD = 0.0049) with all p < 0.001. The main effect for lighting level (F (1, 700) = 5.403, p = 0.020) does not reach statistical significance in accordance with a significance level of 0.001 due to the violation to the assumption of homogeneity of variance at a significance level of 0.05. The interaction effect between step-height and lighting level is not statistically significant (F (7, 700) = 1.851, p = 0.075). Direction is a significant factor with F (1, 700) = 17.723, p < 0.001 and effect size of 0.024. Descending step-heights (M = 0.0151, SD = 0.0073) has greater standard deviation than ascending step-heights (M = 0.0132, SD = 0.0044) at p < 0.001 (see Table 4-19).

Older participants

There is a statistically significant main effect for step-height, F (7, 744) = 12.513, p <0.001, with the effect size (Partial Eta Squared) of 0.105. Post-hoc comparison tests reveal that standard deviation of swing time for -125 mm (M = 0.0219, SD = 0.0110) is significantly greater than -30 mm (M = 0.0159, SD = 0.0073), +30 mm (M = 0.0148, SD =

0.0057), +60 mm (*M* = 0.0144, *SD* = 0.0055), +90 mm (*M* = 0.0142, *SD* = 0.0050) and +125 mm (*M* = 0.0152, *SD* = 0.0058) each with $p < 0.001$. Standard deviation for -90 mm (*M* = 0.0195, *SD* = 0.0097) is also significantly greater than +60 mm (*M* = 0.0144, *SD* = 0.0055) and +90 mm (*M* = 0.0142, *SD* = 0.0050) each with $p < 0.001$. The main effect for lighting level (F (1, 744) = 2.881, p = 0.090) does not reach statistical significance. The interaction effect between step-height and lighting level was not statistically significant (F (7, 744) = 0.599, p = 0.757). Direction was a significant factor with F (1, 744) = 54.525, $p < 0.001$ and effect size of 0.067. Descending step-heights (*M* = 0.0188, *SD* = 0.0096) has greater standard deviation than ascending step-heights (*M* = 0.0147, *SD* = 0.0055) at $p < 0.001$ (see Table 4-19).

Table 4-19: Standard deviation of swing time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0177	0.0154	0.0136	0.0138	0.0127	0.0132	0.0131	0.0139
Old	0.0219	0.0195	0.0181	0.0159	0.0148	0.0144	0.0142	0.0152
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0164	0.0139	0.0125	0.0148	0.0124	0.0124	0.0132	0.0136
Old	0.0208	0.0194	0.0174	0.0146	0.0147	0.0146	0.0144	0.0144
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0191	0.0169	0.0146	0.0127	0.0130	0.0140	0.0129	0.0142
Old	0.0231	0.0196	0.0187	0.0173	0.0149	0.0143	0.0139	0.0160

Cluster analysis

The standard deviation of swing time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is two and participants in Cluster 1 (n = 29) tend to have smaller standard deviation than those in Cluster 2 (n = 2).

A Chi-square test for independence indicates significant association between age and clustering outcome, χ^2 (1, n = 31) = 2.004, p = 0.0096. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 2.004, p = 0.0096. The association between glasses and clustering outcome reached statistical significance, χ^2 (1, n = 31) = 5.226, p = 0.021. Those who wore glasses tend to have greater standard deviation. It is worth to note that the two participants in Cluster 2 are both older females with glasses.

Summary

The summary of statistical analysis of the standard deviation of swing time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):

Young participants – step-heights (-125mm had greater standard deviation of swing time than -60, -30, +30, +60, +90 and +125mm), direction (descending step-heights had greater standard deviation of swing time than ascending step-heights);

Older participants – step-heights (-125mm had greater standard deviation of swing time than -30, +30, +60, +90 and +125mm; -90mm and greater standard deviation of swing time than +60 and +90mm), direction (descending step-heights had greater standard deviation of swing time than ascending step-heights);

Cluster analysis – glasses (those who wore glasses tended to have greater standard deviation of swing time).

4.4.4.3 Coefficient of variation of swing time

Young participants

There is a statistically significant main effect for step-height, F (7, 700) = 6.479, p <0.001, with the effect size (Partial Eta Squared) of 0.61. Post-hoc comparison tests reveal that coefficient of variation of swing time for -125 mm (M = 0.0397, SD = 0.0205) is significantly greater than -60 mm (M = 0.0306, SD = 0.0135), -30 mm (M = 0.0313, SD = 0.0126), +30 mm (M = 0.0287, SD = 0.0071), +60 mm (M = 0.0302, SD = 0.0098) and +90 mm (M = 0.0296, SD = 0.0111) with all p < 0.001. The main effect for lighting level (F (1, 700) = 4.359, p = 0.037) does not reach statistical significance in accordance with a significance level of 0.001 due to the violation to the assumption of homogeneity of variance at a significance level of 0.05. The interaction effect between step-height and lighting level is not statistically significant (F (7, 700) = 2.089, p = 0.043) in accordance with the significance level of 0.01. Direction is a significant factor with *F* (1, 700) = 16.347, $p < 0.001$ and effect size of 0.022. Descending step-heights (*M* = 0.0340, *SD* = 0.0163) has greater coefficient of variation than ascending step-heights (*M* = 0.0300, *SD* = 0.0099) at $p < 0.001$ (see Table 4-20).

Older participants

There is a statistically significant main effect for step-height, *F* (7, 744) = 12.513, p <0.001, with the effect size (Partial Eta Squared) of 0.105. Post-hoc comparison tests reveal that coefficient of variation of swing time for -125 mm (*M* = 0.0480, *SD* = 0.0232) is significantly greater than -30 mm (*M* = 0.0351, *SD* = 0.0167), +30 mm (*M* = 0.0326, *SD* = 0.0133), +60 mm (*M* = 0.0320, *SD* = 0.0127), +90 mm (*M* = 0.0315, *SD* = 0.0113) and +125 mm (*M* = 0.0340, *SD* = 0.0129) with all $p < 0.001$. Coefficient of variation for -90 mm (*M* = 0.0429, *SD* = 0.0218) is also significantly greater than +60 mm (*M* = 0.0320, *SD* = 0.0127) and +90 mm (*M* = 0.0315, *SD* = 0.0113) with both $p < 0.001$. The main effect for lighting level (*F* (1, 744) = 2.881, $p = 0.090$) does not reach statistical significance. The interaction effect between step-height and lighting level is not statistically significant (*F* (7, 744) = 0.599, $p = 0.757$). Direction is a significant factor with *F* (1, 744) = 50.368, $p < 0.001$ and effect size of 0.062. Descending step-heights (*M* = 0.0414, *SD* = 0.0211) has greater coefficient of variation than ascending step-heights (*M* = 0.0325, *SD* = 0.0126) at $p > 0.001$ (see Table 4-20).

Table 4-20: Coefficient of variation of swing time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0397	0.0345	0.0306	0.0313	0.0287	0.0302	0.0296	0.0315
Old	0.0480	0.0429	0.0398	0.0351	0.0326	0.0320	0.0315	0.0340
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0367	0.0311	0.0281	0.0338	0.0282	0.0287	0.0302	0.0311
Old	0.0457	0.0428	0.0384	0.0322	0.0324	0.0323	0.0321	0.0317
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0427	0.0379	0.0332	0.0288	0.0293	0.0317	0.0289	0.0318
Old	0.0505	0.0430	0.0411	0.0380	0.0328	0.0318	0.0309	0.0364

Cluster analysis

The coefficient of variation of swing time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is two and participants in Cluster 1 (n = 27) tend to have smaller coefficient of variation than those in Cluster 2 (n = 4).

A Chi-square test for independence indicates significant association between age and clustering outcome, χ^2 (1, n = 31) = 4.306, p = 0.016. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 1.006, p = 0.305. The association between glasses and clustering outcome reached statistical significance, χ^2 (1, n = 31) =11.226, p = 0.001. Those who wore glasses tend to have a greater standard deviation. It is worth to note that three of the four participants in Cluster 2 are older females with glasses.

Summary

The summary of statistical analysis of the coefficient of variation of swing time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):
Young participants – step-heights (-125mm had greater coefficient of variation of swing time than -60, -30, +30, +60 and +90mm), direction (descending step-heights had greater coefficient of variation than ascending step-heights);
Older participants - step-heights (-125mm had greater coefficient of variation of swing time than -30, +30, +60, +90 and +125mm; -90mm had greater coefficient of variation of swing time than +60 and +90mm), direction (descending step-heights had greater coefficient of variation than ascending step-heights);
Cluster analysis – glasses (those who wore glasses tended to have greater coefficient of variation of swing time).

4.5 Change in gait variables associated with the first fixation

4.5.1 Double support time

Young participants

There is a statistically significant main effect for step-height, F (7, 543) = 2.142, p = 0.038, with the effect size (Partial Eta Squared) of 0.27. Post-hoc comparison tests reveal that the change in double support time for -90 mm (M = -0.0025, SD = 0.1546) is significantly different from +30 mm (M = 0.0057, SD = 0.1439), with p = 0.02. The main effect for lighting level (F (1, 543) = 1.167, p = 0.281) does not reach statistical significance. The interaction effect between step-height and lighting level is not statistically significant (F (7, 543) = 0.890, p = 0.514). Direction has no significant association with the change with F (1, 543) =2.266 and p = 0.133 (see Table 4-21).

Older participants

There is a non-significant main effect of step-height as well as lighting level on the change in double support time (F (7, 578) = 0.9, p = 0.505, and F (1, 578) = 2.571, p = 0.833, respectively). The interaction effect between step-height and lighting level is not statistically significant (F (7, 578) = 0.296, p = 0.956). Direction has no significant association with the change with F (1, 578) = 0.010 and p = 0.920 (see Table 4-21).

Table 4-21: Change in double support time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	-0.0013	-0.0025	0.0014	0.0028	0.0057	-0.0004	0.0018	0.00005
Old	0.0051	0.0052	0.0092	0.0083	0.0078	0.0045	0.0087	0.0073
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	-0.0010	-0.0031	-0.0004	0.0022	0.0081	-0.0022	-0.0004	-0.0013
Old	0.0049	0.0039	0.0080	0.0066	0.0060	0.0029	0.0067	0.0084
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	-0.0016	-0.0020	0.0032	0.0032	0.0028	0.0013	0.0043	0.0013
Old	0.0052	0.0065	0.0102	0.0100	0.0095	0.0060	0.0107	0.0064

Cluster analysis

The change in double support time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is two and participants in Cluster 2 (n = 6) tend to have greater change in double support time than those in Cluster 1 (n = 25).

A Chi-square test for independence indicates no significant association between age and clustering outcome, χ^2 (1, n = 31) = 0.675, p = 0.407. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 0.009, p = 0.930. The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 0.067, p = 0.750.

Summary

The summary of statistical analysis of the change in double support time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):
Young participants – step-heights (-90 mm (negative change) was different from +30 mm (positive change));
Older participants – none;
Cluster analysis – none.

4.5.2 Stride time

Young participants

There is a statistically significant main effect for step-height, F (7, 543) = 3.451, p = 0.01, with the effect size (Partial Eta Squared) of 0.43. Post-hoc comparison tests reveal that the change in stride time for -125 mm (M = 0.118, SD = 0.3582) is significantly different from +90 mm (M = -0.0595, SD = 0.2092), with p < 0.001, and the change for -90 mm (M = 0.072, SD = 0.3141) is also significantly different from +90 mm (M = -0.0025, SD = 0.1546), with p = 0.33. There is a statistically significant main effect for lighting level, F (1, 543) = 10.237, p = 0.001, with the effect size of 0.19. The change in stride time for 4lux is negative (M = -0.0097, SD = 0.0252) whereas the change for 200lux is positive (M = 0.0577, SD = 0.0252), which are significantly different from each other at p =

0.001. The interaction effect between step-height and lighting level is not statistically significant (F (7, 543) = 0.730, p = 0.646). Direction is a significant factor with F (1, 543) = 12.671, p < 0.001 and effect size of 0.22. The change in stride time between ascending step-heights (M = -0.0013, SD = 0.0210) and descending step-heights (M = 0.0061, SD = 0.0288) is significantly different at p < 0.001 (see Table 4-22).

Older participants

There is a non-significant main effect of step-height as well as lighting level on the change in stride time (F (7, 578) = 2.007, p = 0.052, and F (1, 578) = 1.414, p = 0.235, respectively).Even though the association between the change in stride time and step-height is not significant, the association could still be seen as noticeable. The interaction effect between step-height and lighting level is not statistically significant (F (7, 578) = 0.268, p = 0.966). Direction is a significant factor with F (1, 578) = 11.177, p = 0.001 with effect size of 0.019. The change in stride time between ascending step-heights (M = 0.0184, SD = 0.0344) and descending step-heights (M = 0.0293, SD = 0.0436) is significantly different at p = 0.001 (see Table 4-22).

Table 4-22: Change in stride time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0018	0.0072	0.0038	0.0009	0.0005	0.0016	-0.0059	-0.0007
Old	0.0327	0.0343	0.0254	0.0251	0.0182	0.0173	0.0205	0.0176
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0131	0.0073	0.0090	0.0041	0.0027	0.0031	-0.0127	0.0066
Old	0.0292	0.0348	0.0223	0.0190	0.0162	0.0192	0.0183	0.0163
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0104	0.0072	-0.0012	-0.0019	-0.0021	0.0002	0.0003	-0.0072
Old	0.0366	0.0337	0.0282	0.0314	0.0201	0.0155	0.0226	0.0187

Cluster analysis

The change in stride time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is four and participants in Cluster 2 (n = 3) tend to have greater change in stride time than those in Cluster 1 (n = 28).

A Chi-square test for independence indicates significant association between age and clustering outcome, χ^2 (1, n = 31) = 3.114, p = 0.039. All of the three participants clustered in Cluster 2 are elderly. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 0.301, *p* = 0.579. The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 2.283, *p* = 0.153.

Summary

The summary of statistical analysis of the change in stride time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):
Young participants – step-heights (-125 mm (negative change) was different from +90 mm (positive change)), lighting level (4lux (negative change) was different from 200lux (positive change)), direction (ascending step-heights (negative change) was different from descending step-heights (positive change));
Older participants – direction (descending step-heights had positive change in stride time greater than ascending step-heights);
Cluster analysis – age (older participants tended to have greater change in stride time).

4.5.3 Stance time

Young participants

There is a non-significant main effect of step-height on the change in stance time (*F* (7, 543) = 1.686, *p* = 0.110. There is a statistically significant main effect for lighting level, *F* (1, 543) = 4.937, *p* = 0.027, with the effect size of 0.09. The change in stance time for 200lux (*M* = 0.0031, *SD* = 0.0149) is significantly greater than 4lux (*M* = 0.002, *SD* = 0.0147) at *p* = 0.027. The interaction effect between step-height and lighting level is not statistically significant (*F* (7, 543) = 0.376, *p* = 0.916). Direction is a significant factor with *F* (1, 543) =5.403, *p* = 0.020 and effect size of 0.010. The change in stance time between ascending step-heights (*M* = 0.0002, *SD* = 0.0133) and descending step-heights (*M* = 0.0031, *SD* = 0.0162) is significantly different at *p* = 0.02 (see Table 4-23).

Older participants

There is a non-significant main effect of step-height as well as lighting level on the change in stance time (F (7, 578) = 1.699, p = 0.106, and F (1, 578) = 1.750, p = 0.186, respectively). The interaction effect between step-height and lighting level is not statistically significant (F (7, 578) = 0.370, p = 0.920). Direction is a significant factor with F (1, 578) = 9.434, p = 0.002 and effect size of 0.16. The change in stance time between ascending step-heights (M = 0.0123, SD = 0.0221) and descending step-heights (M = 0.0181, SD = 0.0244) is significantly different at p = 0.002 (see Table 4-23).

Table 4-23: Change in stance time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0052	0.0024	0.0026	0.0018	0.0031	0.0004	-0.0021	-0.0003
Old	0.0189	0.0197	0.0173	0.0167	0.0124	0.0091	0.0146	0.0127
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0060	0.0022	0.0043	0.0031	0.0054	0.0004	-0.0001	0.0026
Old	0.0171	0.0194	0.0151	0.0128	0.0111	0.0111	0.0129	0.0124
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0044	0.0026	0.0010	0.0007	0.0003	0.0003	-0.0042	-0.0029
Old	0.0209	0.0201	0.0192	0.0207	0.0136	0.0074	0.0167	0.0131

Cluster analysis

The change in stance time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is two and participants in Cluster 2 (n = 3) tend to have greater change in stance time than those in Cluster 1 (n = 28).

A Chi-square test for independence indicates significant association between age and clustering outcome, χ^2 (1, n = 31) = 3.114, p = 0.039. All of the three participants clustered in Cluster 2 are elderly. There is no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 0.301, p = 0.579. The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 2.283, p = 0.153.

Summary

The summary of statistical analysis of the change in stance time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):

Young participants – lighting level (200lux had positive change in stance time greater than 4lux, direction (descending step-heights had positive change in stance time greater than ascending step-heights);

Older participants – direction (descending step-heights had positive change in stance time greater than ascending step-heights);

Cluster analysis – age (older participants tended to have greater change in stance time).

4.5.4 Swing time

Young participants

There is a statistically significant main effect for step-height, F (7, 543) = 4.687, $p <$ 0.001, with the effect size (Partial Eta Squared) of 0.57. Post-hoc comparison tests reveal that the change in swing time for -125 mm (M = 0.0065, SD = 0.0199) is significantly different from -30 mm (M = -0.0092, SD = 0.0111), +30 mm (M = -0.0065, SD = 0.0199) and +90 mm (M = -0.0039, SD = 0.0130), with p = 0.04, 0.03 and $p < 0.001$ respectively, and the change for -90 mm (M = 0.0050, SD = 0.0175) is significantly different from +30 mm (M = -0.0065, SD = 0.0199) and +90 mm (M = -0.0039, SD = 0.0130), with p = 0.037 and 0.005 respectively. There is a statistically significant main effect for lighting level, F (1, 543) = 11.930, p = 0.001, with the effect size of 0.22. The change in swing time for 4lux is negative (M = -0.0014, SD = 0.0146) whereas the change for 200lux is positive (M = 0.0027, SD = 0.0143) at p = 0.001, which are significantly different from each other. The interaction effect between step-height and lighting level is not statistically significant (F (7, 543) = 1.148, p = 0.331). Direction is a significant factor with F (1, 543) = 15.666, $p < 0.001$ and effect size of 0.27. The change in swing time between ascending step-heights (M = -0.0017, SD = 0.0127) and descending step-heights (M = 0.0031, SD = 0.0160) is significantly different at $p < 0.001$ (see Table 4-24).

Older participants

There is a statistically significant main effect for step-height, *F* (7, 578) = 2.570, *p* = 0.013, with the effect size (Partial Eta Squared) of 0.30. Post-hoc comparison tests reveal that the change in swing time for -90 mm (*M* = 0.1451, *SD* = 0.0254) is noticeably greater from +30 mm (*M* = 0.0052, *SD* = 0.0185) and +125 mm (*M* = 0.0051, *SD* = 0.0177), with *p* = 0.088 and 0.079 respectively. Because of small sample size, the correlation is not reflected in the significance value in the post-hoc test even though the analysis of variance test reveals significant main effect for step-height. The main effect for lighting level (*F* (1, 578) = 1.096, *p* = 0.335) does not reach statistical significance. The interaction effect between step-height and lighting level is not statistically significant (*F* (7, 578) = 0.286, *p* = 0.959). Direction is a significant factor with *F* (1, 578) = 11.462, *p* = 0.001 and effect size of 0.19. The change in swing time between ascending step-heights (*M* = 0.0056, *SD* = 0.0177) and descending step-heights (*M* = 0.0111, *SD* = 0.0219) is significantly different at *p* = 0.001 (see Table 4-24).

Table 4-24: Change in swing time (unit: second).

Overall	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0065	0.0050	0.0012	-0.0009	-0.0025	0.0005	-0.0039	-0.0004
Old	0.0138	0.0145	0.0081	0.0084	0.0052	0.0064	0.0059	0.0052
200lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0070	0.0053	0.0047	0.0009	-0.0027	0.0027	0.0004	0.0040
Old	0.0122	0.0154	0.0071	0.0062	0.0051	0.0082	0.0058	0.0062
4lux	**-125mm**	**-90mm**	**-60mm**	**-30mm**	**+30mm**	**+60mm**	**+90mm**	**+125mm**
Young	0.0060	0.0047	-0.0022	-0.0026	-0.0024	-0.0015	-0.0085	-0.0042
Old	0.0157	0.0136	0.0090	0.0107	0.0053	0.0048	0.0059	0.0040

Cluster analysis

The change in swing time is standardised (z-score) for cluster analysis to allow for different metrics in which the performance is measured. The number of clusters is initially set to be four and then narrowed down to two to test for the skewedness of the distribution of number of participants in each cluster. The final number of clusters is two and participants in Cluster 2 (n = 4) tend to have greater change in swing time than those in Cluster 1 (n = 27).

A Chi-square test for independence indicates no significant association between age and clustering outcome, χ^2 (1, n = 31) = 1.006, p = 0.305. In spite of small sample size as well as number of participants in each cluster, 75% of participants in Cluster 2 are elderly, which may be noticeable even though non-significant. There is also no significant association between gender and clustering outcome, χ^2 (1, n = 31) = 0.005, p = 0.945. The association between glasses and clustering outcome does not reach statistical significance, χ^2 (1, n = 31) = 0.980, p = 0.342.

Summary

The summary of statistical analysis of the change in swing time is as follows (for each age group, factors with statistically significant association, with significant post-hoc comparison test results in the brackets, are presented):

Young participants – step-heights (-125 mm (positive change) was different from -30 (negative change), +30 (negative change) and +90 mm (negative change); -90 mm (positive change) was different from +30 (negative change) and +90 mm (negative change)), lighting level (4lux (negative change) was different from 200luix (positive change)), direction (ascending step-heights were different from descending step-heights (positive change));

Older participants – step-heights (-90 mm had positive change in swing time noticeably greater than +30 and +125 mm), direction (ascending step-heights had positive change in swing time greater than descending step-heights);

Cluster analysis – none.

4.6 Conclusion

This chapter has presented the results of the validation of instrumentational synchronisation and statistical analysis. The synchronisation has been proved to be robust and successfully integrated gaze, gait and light gate data. The conclusions of the statistical analysis are as follows:

Gaze behaviour

Young participants' gaze behaviour tends to be associated with step-heights and/or direction, especially in the number of fixations (with +125mm that highest and -60mm the lowest) and total fixation time (with +125mm the longest and -60 as well as -90 mm the shortest).

Older participants' gaze behaviour tends to be associated with lighting levels, especially in mean fixation duration (longer at 4lux), total gaze time (longer at 200lux) and early total gaze time (earlier at 200lux).

There is association between gaze behaviour and trial effect (behaviours in Trial 1 were greater than Trial 2 and/or Trial 3) in both young and older participants, but older participants tended to have more gaze variables associated with trial effect (number of fixations, total fixation time, total gaze time and early total gaze time) than young participants (total fixation time and total gaze time).

The result of the cluster analysis shows that those who wore glasses might be associated with shorter mean fixation duration, shorter total fixation time and later late total gaze time.

Gait pattern

The result of the double support time analysis suggests that older participants tended to have longer mean double support time at 200lux and greater coefficient of variation for descending step-heights; young participants tended to have greater standard deviation at 4lux and for ascending step-heights.

The result of the stride time analysis suggests that both young and old age groups tended to have longer mean stride time at 4lux, the greatest standard deviation as well as coefficient of variation for -125mm and greater standard deviation as well as coefficient of variation for descending step-heights. The result of the cluster analysis shows that those who wore glasses might be associated with a smaller coefficient of variation.

The result of the stance time analysis suggests that both young and old age groups tended to have longer mean stance time at 4lux, the greatest standard deviation as well as coefficient of variation for -125mm and greater standard deviation as well as coefficient of variation for descending step-heights.

The result of the swing time analysis suggests that both young and old age groups tended to have the greatest standard deviation as well as coefficient of variation for -125mm and greater standard deviation as well as coefficient of variation for descending step-heights. The result of the cluster analysis shows that those who wore glasses might be associated with greater standard deviation and coefficient of variation.

Change in gait variables associated with the first visual fixation

Young participants’ change in gait variables tends to be associated with step-heights, lighting levels and direction to different extents. Step-height is associated with the change in double support time (with the greatest difference between -90 and +30mm), stride time (with the greatest difference between -125 and +90mm) and swing time (with the greatest positive change for -125mm among all step-heights). Lighting level is associated with stride time (with an increase at 200lux but a decrease at 4lux), stance time (positively greater at 200lux) and swing time (with an increase at 200lux and a decrease at 4lux). Direction is associated with stride time (with an increase for descending step-heights and a decrease for ascending step-heights), stance time (positively greater for descending step-heights) and swing time (with an increase for descending step-heights and a decrease for ascending step-heights)

Older participants’ change in gait variables tends to be associated with direction, especially in stride time (greater for descending step-heights), stance time (greater for descending step-heights) and swing time (greater for ascending step-heights). For older participants, the step-height of -90 mm had the greatest increase in swing time.

The result of the cluster analysis shows that those who wore glasses tended to have greater positive change in stride time and stance time.

In summary, the result of the statistical analysis comprises very fine grained information about gaze and gait behaviour. For gaze behaviour, young participants were more likely to be affected by step-heights and direction whereas older participants were more likely to be affected by lighting level. The two age groups tended to have similar trends in the results of gait pattern analysis but the change in gait patterns associated with the first visual fixation shows that young participants were more likely to be affected by all environmental factors.

In the following three chapters, the results of the statistical analysis described in this chapter, coupled with descriptive analysis, will be explained in detail. Chapter 5 will present the overall results as well as discussion on gaze behaviour. Chapter 6 will present the overall results as well as discussion on gait behaviour. Chapter 7 will bring gaze behaviour and gait pattern together to present the interaction between these two behaviours and details the implications for footway design.

Chapter 5: Results and discussion on gaze behaviour

This thesis aims to understand how environmental factors, step-height and lighting level, affect participants' visual perception and gait adjustments whilst walking towards an upcoming step-height in a given lighting level. This is treated in three parts: gaze behaviour is discussed in this chapter, gait pattern in Chapter 6 and the combination of gaze and gait behaviours in Chapter 7.

Gaze is important as it is the first means of detection of an obstacle in the environment – if the object is not detected there will be no mechanical reaction in the lower limbs. As discussed in Chapter 3, experiments were conducted to obtain data pertaining to six gaze variables: the number of fixations, mean fixation duration (mean duration for each fixation), total fixation time (aggregation of all fixation durations in the same trial), total gaze time (the time between the early total gaze time and late total gaze time), early total gaze time (the start of the first fixation) and late total gaze time (the end of the last fixation). A way of considering gaze behaviour for this purpose has been described in Section 3.2.2.1 Gaze matrix (see Figure 3-2). The gaze matrix is used to explain the gaze behaviours of number of fixations and mean fixation duration. Gaze behaviours of two age groups, young (see Section 5.1) and older (see Section 5.2) people, are explained followed by the discussion on the results of cluster analysis (see Section 5.3).

5.1 Young participants

The discussion on the gaze behaviour for young participants in relation to the six gaze variables of the number of fixations (Section 5.1.1 and 5.1.2), mean fixation duration (Section 5.1.1 and 5.1.2), total fixation time (Section 5.1.3) and total gaze time, including early total gaze time and late total gaze time (Section 5.1.4), is detailed in the following sections. The possible coping strategy established by the gaze behaviour is then summarised in the conclusion (Section 5.1.5).

5.1.1 Number of fixations and mean fixation duration

The step-heights of +90 and +125 mm in the High-Attention Group (see Figure 5-1 for discussions in this section) show that participants needed to return their gaze back more often for longer than other step-heights, implying these two step-heights might require more precise gait adjustments. It could also imply that the capability required by the step-heights exceeds participants' physical capability for lifting their foot to cross the step-height. The two step-heights in the Low-Attention Group, -60 and -90 mm, reflected a lack of available information to the visual field due to the nature of descending step-heights. The insufficient visual information provided by these two step-heights limited participants capability for detection and measurement. The difference in the number of fixations between +125 and -60 mm as well as +125 and -90 mm did reach significance level (each with $p = 0.001$), and the two groups they fell into registering opposite gaze behaviour. As +125 mm was particularly conspicuous and considerable in height, the increase in both variables was understandable, whereas -60 and -90 mm appeared to provide the most deficient visual information among all step-heights.

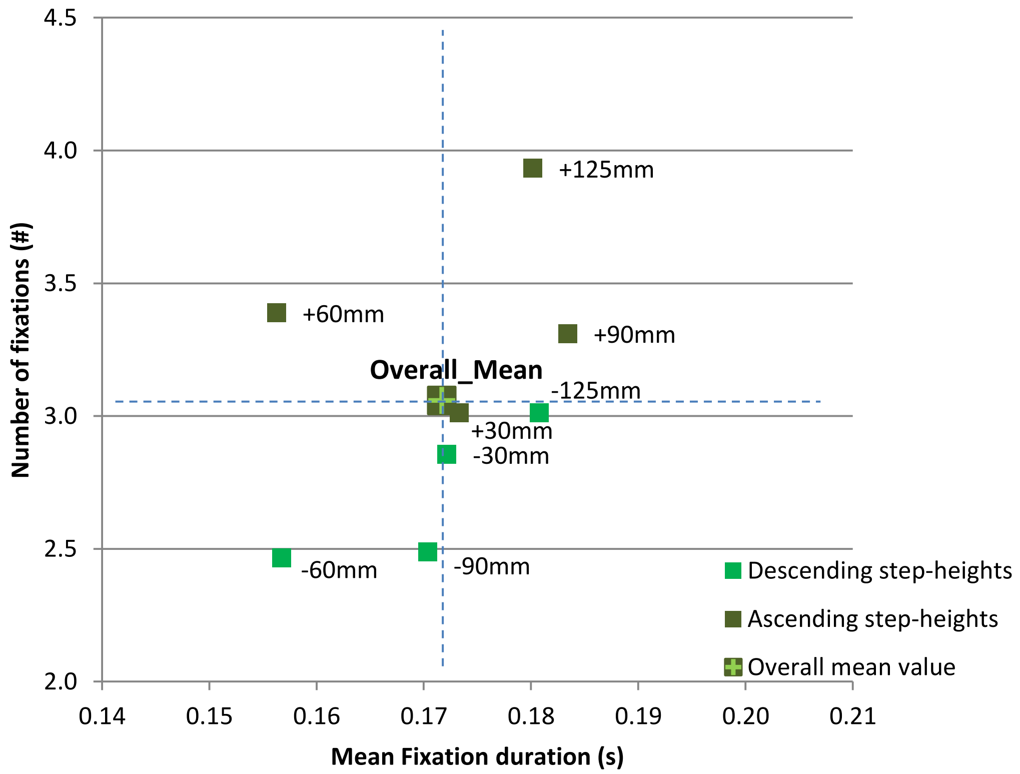


Figure 5-1: Gaze behaviour of the number of fixations and fixation duration for young participants

As the only step-height in the Checking Group, +60 mm had more fixations but shorter mean duration, indicating that +60 mm might be perceived to require an increase in participants' physical capability of gait adjustments but its dimension did not demand longer processing time than more considerable ascending step-heights. In comparison to +90 mm, even though +60 mm shared a similar number of fixations, the duration for +60 mm was noticeably shorter. It might suggest that among ascending step-heights, +60 mm, as opposed to +30 mm having a mean value close to overall mean value, was high enough to increase returned fixations but not until +90 mm that participants' physical capability was not being challenged in terms of gait adjustments.

The Calculating Group consists of -125 and -30 mm with the latter being close to the mean value. A lower number of fixations for -125 mm might be caused by the ambiguity of visibility of the nature of descending step-heights. In comparison to +125 mm, both -125 and +125 mm had longer fixation duration as the heights demanded more time for measurement but the ascending +125 mm had an advantage of the availability of visibility.

When all descending step-heights were investigated as a whole, it might be understandable that due to a lack of availability of visual information, all of them had a lower than average number of fixations. However, -125 mm might be so considerable that participants might have noticed it by deducing from other visual information in the immediate environment, such as the shade of the surface further down the landing phase after the step-height, whereas -60 and -90 mm were perceived to be inconspicuous or not perceived at all.

5.1.2 Effects of lighting level on number of fixations and mean fixation duration

The break-down comparison between lighting levels revealed that both the number of fixations and fixation duration were noticeably greater in 4lux than 200lux. This demonstrated that participants might increase overall visual fixations in order to acquire more visual information in a lower lighting environment (see Figure 5-2 for discussions in this section). It might suggest that at the 4lux lighting level, participants made more efforts to search for step-heights. The Searching Mode, as defined in this thesis based on the gaze behaviour at 4lux, was activated; however it does not mean step-heights in 200lux were not being detected or searched, rather that the activity of searching was more likely to be stimulated by 4lux lighting level.

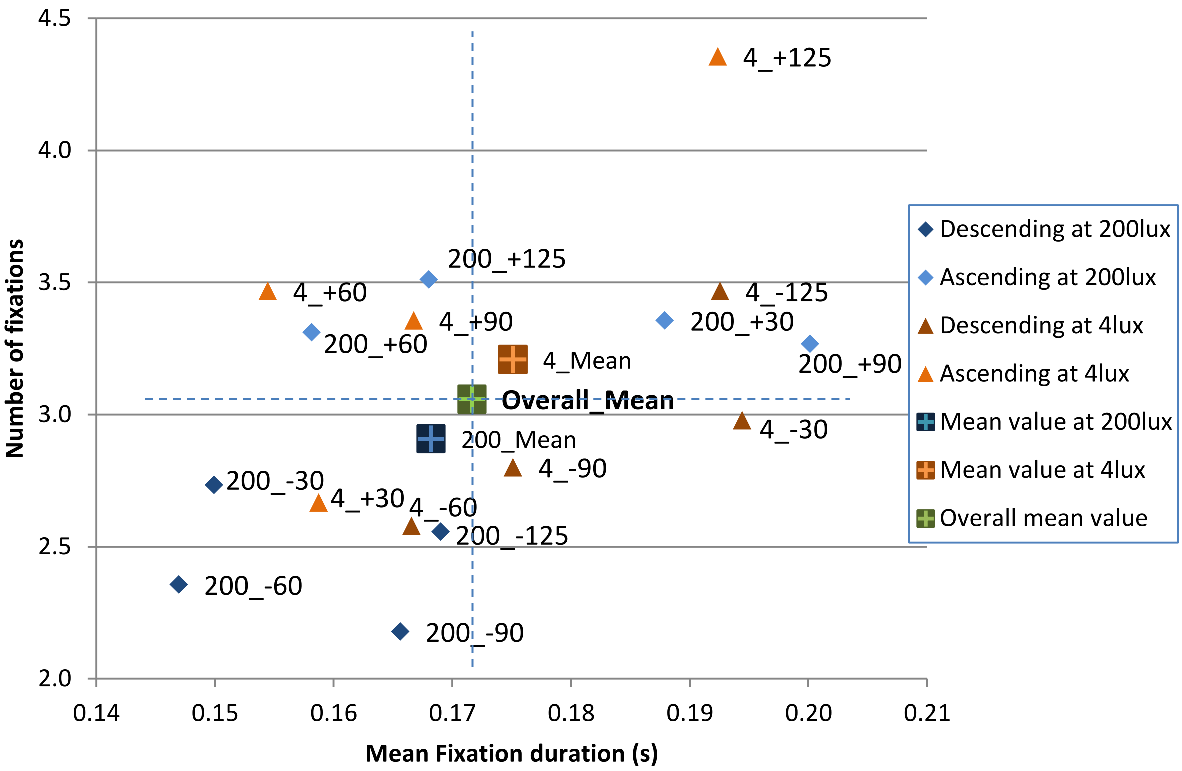


Figure 5-2: Gaze behaviour of the number of fixations and fixation duration for young participants at differently lighting levels.

In the 4lux environment, the two most considerable heights, -125 and +125 mm, fell into the High-Attention Group. Even though +125 mm had more fixations that -125 mm due to the merits of availability of visibility as an ascending step-height, both step-heights were so considerable that increased visual fixations were made by participants. Step-heights of +30 and -60 mm in the Low-Attention Group could be explained that the former was too subtle to detect and the latter provided deficient visual information caused by the descending direction. A step-height of +60 mm in the Checking Group might act as a threshold of visual awareness like its attribute in the overall gaze behaviour detailed in Section 5.1.1. The step-height of -30 mm in the Calculating Group indicates that an increased time might be needed to identify its dimension due to the subtly and low colour contrast; however, +30 mm might be perceived as even more subtler than -30 mm and could be too subtle to detect. It is noteworthy that while +30 mm fell into the Low-Attention Group, -30 mm was in the Calculating Group, which contrasted with the result found at 200lux and will be further discussed in the following subsections.

In the 200lux environment, the High-Attention Group consisted of +30 and +90 mm with the former requiring increased mean fixation duration to detect the subtly as well as low contrast, and the latter being noticeably considerable. The step-height of +125, in spite of falling at the border between the High-Attention and the Checking Groups, had the highest number of fixations, revealing that participants might also perceive it as more physically demanding to overcome. The deficiency of available visual information was reflected by the fact that all descending step-heights constituted the Low-Attention Group. The step-height of +60 mm again consistently demonstrated its role as the threshold of visual awareness.

As previously discussed about the gaze behaviour at 4lux towards the subtle +30 and -30 mm, participants perceived these two step-heights in the opposite way. In the 200lux environment, +30 mm required increased time to be identified whereas -30 could be too subtle to notice. One possible reason for the difference in gaze behaviour could be the consequence of the effects of lighting level. The merit of visibility of the ascending step-height of +30 mm in 200lux was more likely to provide more visual information as opposed to the descending -30 mm. However, the +30 mm in 4lux became less visible than in 200lux but -30 mm was more likely to be detected, possibly thanks to the benefit of the Searching Mode. This suggests that the gaze behaviour towards the subtle heights of +30 and -30 mm might be more likely than other more considerably visible heights to be affected by lighting level.

5.1.3 Total Fixation Time

The total fixation time across all step-heights showed a similar pattern to the gaze behaviour of the number of fixations (see Figure 5-3 for discussions in this section). The step-height of +125 mm had the longest time period whereas -60 and -90 mm were fixated by the two shortest time periods. The difference between +125 and -60 mm as well as +125 and -90 mm reached a statistically significant level (with p = 0.005 and 0.002 respectively). The conspicuous visual information for +125 mm acquired a longer fixation time period, but the ambiguity in visibility of descending step-heights caused a decrease in the fixation time for -60 and -90 mm. Participants also made longer total fixation time for considerable heights of +90 and -125 mm that were possibly more likely to require more gait adjustments. The total fixation time suggested that +125, +90, and -125 mm might be the step-heights demanding more physical capability, whereas -60 and -90 mm were possibly the two most visually ambiguous heights.

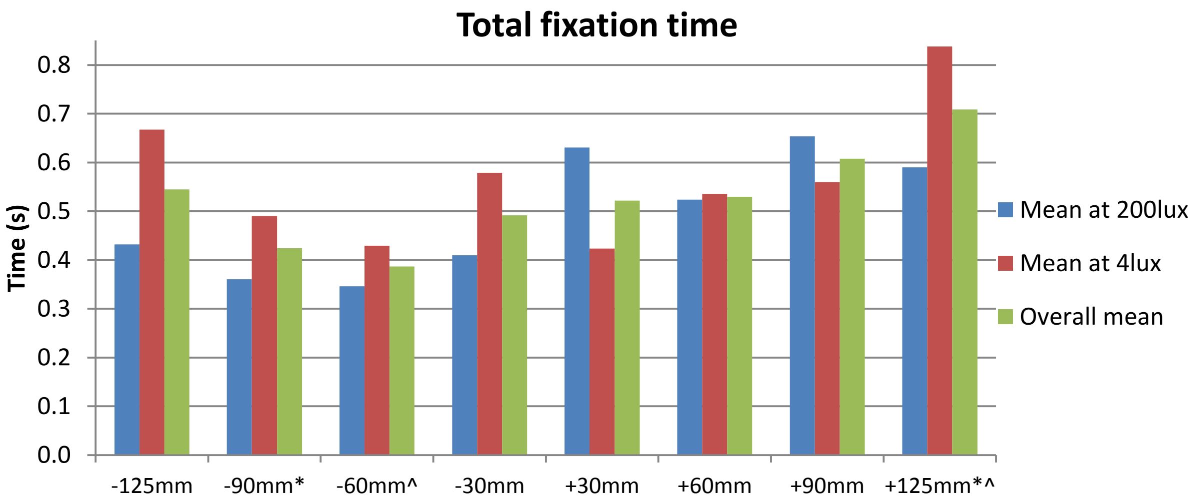


Figure 5-3: The total fixation time for young participants.
(* and ^ indicate a statistically significant correlation ($p < 0.05$) in number of fixations.)

The break-down comparison between two lighting levels further revealed that when the Searching Mode was activated in 4lux, descending step-heights were fixated longer than they were in 200lux. The gaze behaviour suggested that even though the overall total fixation time for descending step-heights was shorter than ascending step-heights due to the deficiency of visual information, participants did make more efforts for detection in 4lux and it also showed how the detection of descending step-heights benefited from the Searching Mode.

5.1.4 Total gaze time

The total gaze time did not show any statistically significant pattern. Neither the early nor the late total gaze time was significantly correlated to step-height or lighting level. However, the total gaze time was noticeably shorter for descending step-heights than ascending step-heights, which might be caused by the deficiency of visual information (see Figure 5-4).

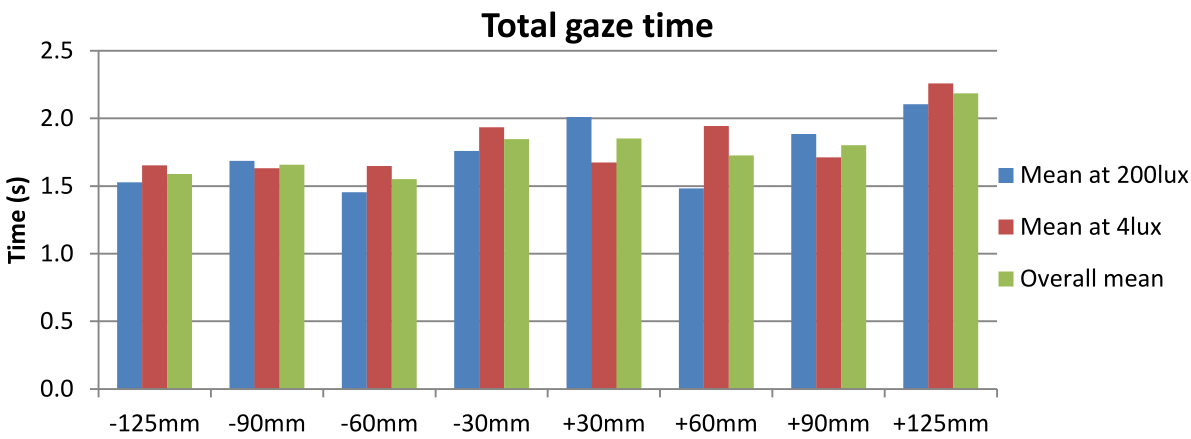


Figure 5-4: The total gaze time for young participants.

Trial effect was found in the total gaze time. Trial 1 was longer than the following two trials, particularly significantly longer than Trial 3 (p = 0.04). The decrease in gaze time suggested that participants might gradually learn to coordinate visual information with cognitive processing and/or gait adjustments as trials went. Participant could be benefit from the trial effect by reacting to the step-height and then planning their gait adjustments more efficiently.

5.1.5 Conclusion of gaze behaviour of young participants

In summary, young participants' gaze behaviour could be interpreted by the six gaze variables analysed in this thesis and the discussion suggested that each step-height could reflect a particular visual perception and imply potential gait adjustments (see Table 5-1).

Step-heights of +125, +90 and -125 mm were so conspicuous in height that they might require more precise gait adjustments. Step-height of +60 mm might be a threshold of visual awareness whereas +90 mm might be a threshold of physical capability of gait adjustments. Descending step-heights of -60 and -90 mm were more visually ambiguous, which might also be regarded potential dangers. The perception of subtle step-heights of +30 and -30 mm was likely to be affected by lighting level, and therefore gait adjustments might be affected accordingly. The 4lux lighting environment, in general, activated the Searching Mode, causing increased visual detection, and the descending step-heights in 4lux noticeably made use of the Mode.

Table 5-1: Summary of the gaze behaviour for young participants.

-125 mm	-90 mm * +	-60 mm ^ #	-30 mm	+30 mm	+60 mm	+90 mm	+125 mm * ^ & #
High-Attention Group	Low-Attention Group	Low-Attention Group	Calculating Group	Calculating Group	Checking Group	High-Attention Group	High-Attention Group
Visually noticeable	Visually ambiguous	Visually ambiguous	Affected by lighting level (ambiguous at 200lux)	Affected by lighting level (ambiguous at 4lux)	Visual noticeable (possible visual awareness threshold)	Visually noticeable	Visually noticeable

1) Searching Mode was activated in 4lux, especially for descending step-heights.
2) Descending step-heights were possibly more visually ambiguous.
3) The trial effect showed that young participants might save total gaze time for possibly related cognitive processing and/or gait adjustments as trials went %.

* and ^ indicate a significant correlation ($p < 0.05$) in number of fixations between step-heights.
& and # indicate a significant correlation ($p < 0.05$) in total fixation time between step-heights.
% indicated a significant correlation ($p < 0.05$).

The overall gaze behaviour suggested that young participants implemented a coping strategy to counteract the deficiency of visibility of step-heights in 4lux by increasing detection and processing time. The implementation of this strategy was especially more noticeable among descending step-heights. The trial effect suggested that the familiarity of the environment might also help plan as well as implement the strategy in advance (which will be further discussed in the interaction between gaze and gait behaviours in Chapter 7).

5.2 Older participants

The discussion on the gaze behaviour for older participants in relation to the six gaze variables of the number of fixations (Section 5.2.1 and 5.2.2), mean fixation duration (Section 5.2.1 and 5.2.2), total fixation time (Section 5.2.3) and total gaze time, including early total gaze time and late total gaze time, (Section 5.2.4) is detailed in the following sections. The possible coping strategy established by the gaze behaviour is then summarised in the conclusion (5.2.5).

5.2.1 Number of fixations and mean fixation duration

The gaze variables of the number of fixations and fixation duration were not significantly affected by step-heights and older participants demonstrated behaviours clustered closer to the mean value as opposed to young participants (see Figure 5-5 for discussions in this section). The discussion on the difference in gaze behaviour between two age groups will be further elaborated in discussions on coping strategies in sections 5.2.5 and 5.4. Nevertheless, within the group of older participants there was indeed a variety of distinctive gaze behaviour which is worth discussing.

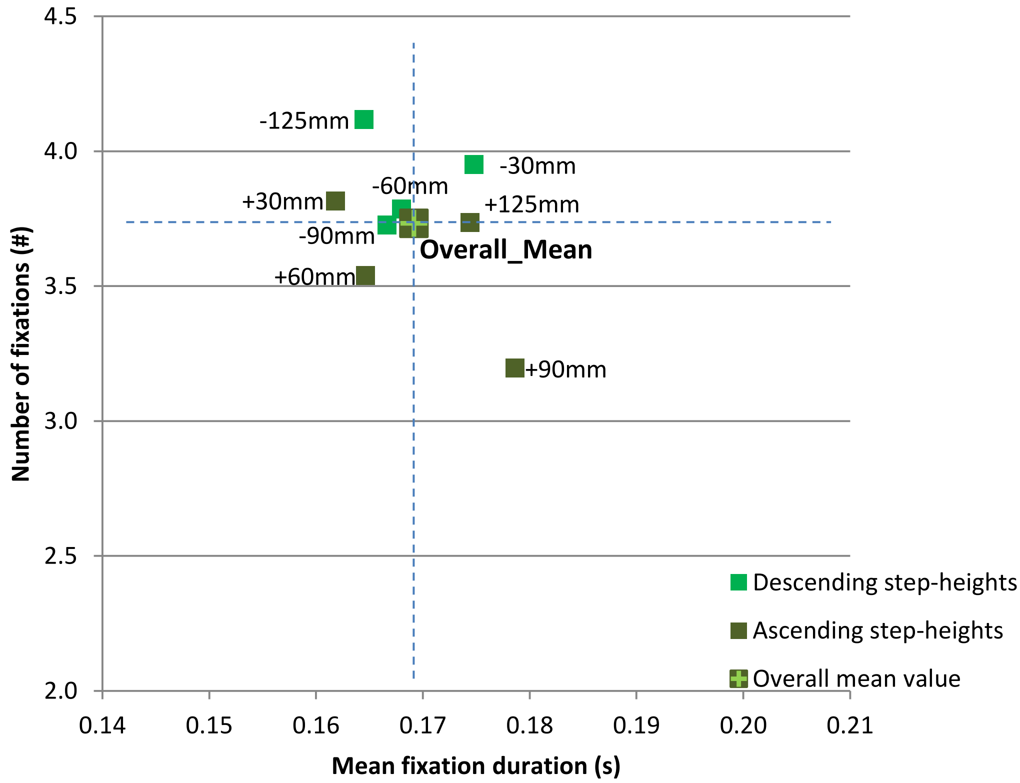


Figure 5-5: Gaze behaviour of the number of fixations and fixation duration for older participants

The High-Attention Group reflected a greater amount of visual information acquired by participants, yet the two step-heights constituting this Group showed different types of capability required. The step-height of +125 mm appeared to be too considerable that participants needed more visual information to make precise gait adjustments whereas the subtle and low contrast -30 mm also caused more visual fixations. Previous studies on obstacle avoidance have showed that both considerable and subtle heights could possibly demand increased visual information (Patla and Vickers, 1997), suggesting that participants needed to make more efforts to identify the dimension of obstacles. This finding could also be applied to step-heights of +125 and -30 mm. The step-height of 60 mm falling into the Low-Attention Group seemed to contradict its natural availability of visual information. It could be possibly explained that +60 mm for older participants was more likely to be detected and also to be overcome by gait adjustments than most of the step-heights, so that fewer fixations were made and of shorter duration.

The step-height in the Calculating Group, +90 mm, showed that the dimension of the +90 mm needed increased visual processing demand, which might suggest that the cognitive and/or gait adjustments required more visual information for developing corresponding coping strategy. The step-heights of -125 and +30 mm in the Checking Group reflected increased returned fixations, which could be the case that participants perceived -125 mm to be considerably high and +30 mm to be dangerously subtle. The gaze behaviour towards step-heights of -125 and +30 mm seemed in line with the behaviour towards +125 and -30 mm in the High-Attention Group in spite of a moderate decrease in mean fixation duration for the Checking Group. The similarity suggests that the height of $\pm$125 mm might demand more cognitive processing and/or gait adjustments due to its considerable height and the ambiguity of $\pm$30 mm might demand more time for detection and measurement. Both heights might potentially be perceived as dangers in the footway environment yet with different attributes.

The descending step-heights in general had more fixations as opposed to ascending step-heights and might be perceived as more dangerous than ascending step-heights. In comparison with -125 and -30 mm, the other two descending step-heights of -60 and -90 mm had comparatively fewer fixations. As previously discussed, the attributes of -30 and -125 mm were more likely to require more fixations, -60 and -90 mm seemed to be either less visually ambiguous and/or less challenging to gait adjustments. However, the fact that all descending step-heights had increased fixations suggested that a lack of availability of visual information about the dimension of step-heights actually redirected older participants' gaze back more often as opposed to young participants.

It has to be borne in mind that the difference in the number of fixations for older participants was less noticeable in comparison with young participants. It could be possible that however subtle or considerable the step-height was, older participants consistently made efforts to acquire a certain level of visual information by returned gaze. This coping strategy will be further discussed in Section 5.2.3, in which the total fixation time registered a similar trend.

Trial effect was found in the gait variable of the number of fixations. Previous studies have revealed that older people tended to shift away their gaze from the first to the following stepping target earlier than younger people (Chapman and Hollands, 2010; Hollands et al., 2002; Young and Hollands, 2010). These studies suggested that the gait adjustment was the main reason for the early gaze shift, by which older people could start planning their gait coping strategy earlier. This thesis revealed the coping strategy of making use of trial effect, thus echoing the previous studies. Older participants seemed to give more of their cognitive processing to implement a coping strategy, maybe because they were trading the overall fixation time for planning coping strategy by exploiting the familiarity with the environment.

5.2.2 Effects of lighting level on number of fixations and mean fixation duration

The fixation duration was significantly associated with lighting level and the 4lux had longer mean fixation duration than 200lux (p = 0.036). It revealed that the Searching Mode found in the gaze behaviour of young participants (Section 5.1.2) was also used by older participants. However, the Searching Mode for older participants was activated across all step-heights as opposed to mainly for descending step-heights for young participants (see Figure 5-6 for discussions in this section).

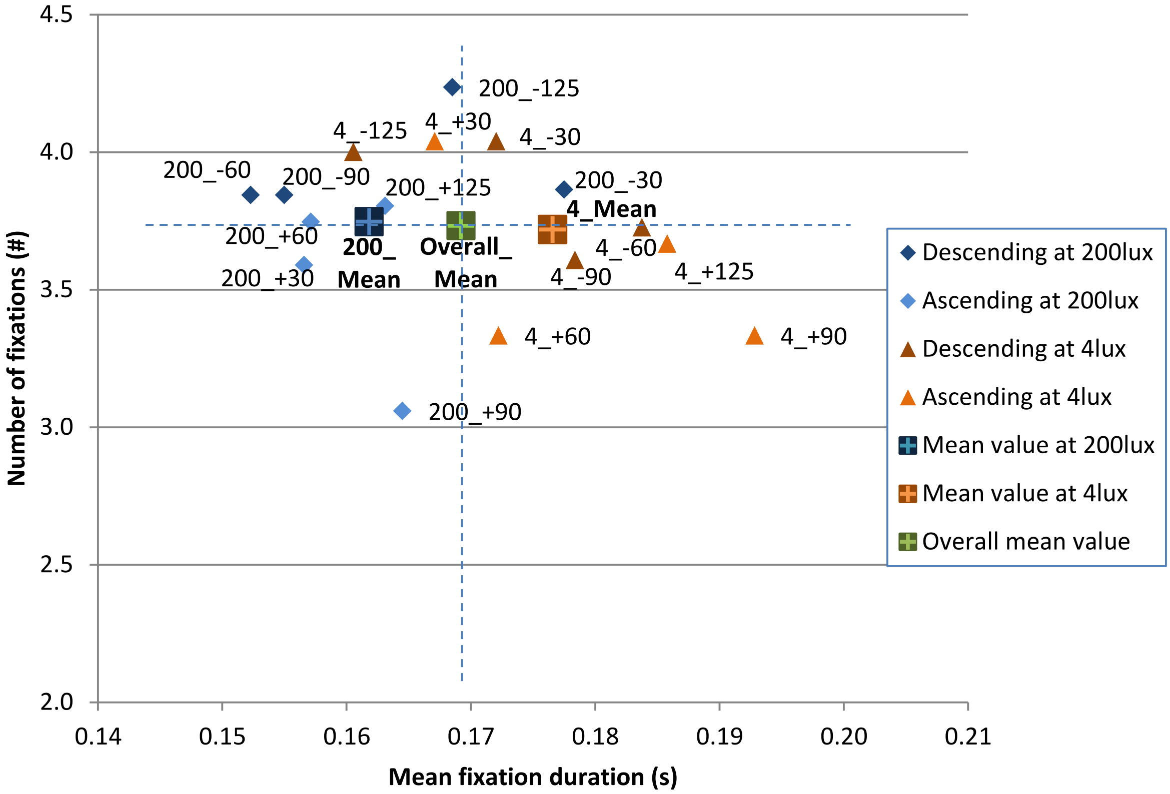


Figure 5-6: Gaze behaviour of the number of fixations and fixation duration for older participants at differently lighting levels.

In 4lux, most of step-heights fell into either the Checking or Calculating Group. In the Checking group, the step-heights of -125, +30 and +125 mm were either considerable or subtle enough to acquire longer mean duration. The step-heights in the Calculating Group, -90, +60, +125, +90 were of greater dimension in height. It is noteworthy that +60 and +90 mm had the same number of fixations, but +90 mm required greater visual processing demand than +60 mm, indicating more precise cognitive processing and/or gait adjustments might be needed to overcome +90 mm.

In 200lux, the number of fixations as well as the fixation duration did not vary between most of the step-heights. However, the attribute of -125 and -30 mm in the High-Attention Group (with -125 mm on the border of High-Attention and Checking Groups) was found to be in line with the previous discussion as well as Section 5.2.1. The step-height of +90 mm in 200lux seemed to be detectable but requiring more precise visual information for cognitive processing and/or gait adjustments accordingly.

5.2.3 Total fixation time

The total fixation time showed a “W” pattern across all step-heights (see Figure 5-7). Among ascending step-heights, +30 and +125 mm had longer overall time than +60 and +90 mm, and among descending step-heights, -30 and -125 mm were the step-heights with the longest overall time. It is suggested that the heights of $\pm$125 and $\pm$30 mm both demanded more visual information and were possibly perceived as more dangerous with the former being considerably high and the latter being visibly subtle, further supporting the findings in Section 5.2.1 and 5.2.2. The comparison between ascending and descending step-heights showed that older participants noticeably increased total fixation time for descending step-height. It could be the case that older participants might counteract the ambiguity of the visibility of the descending step-heights by increasing the overall visual processing demands.

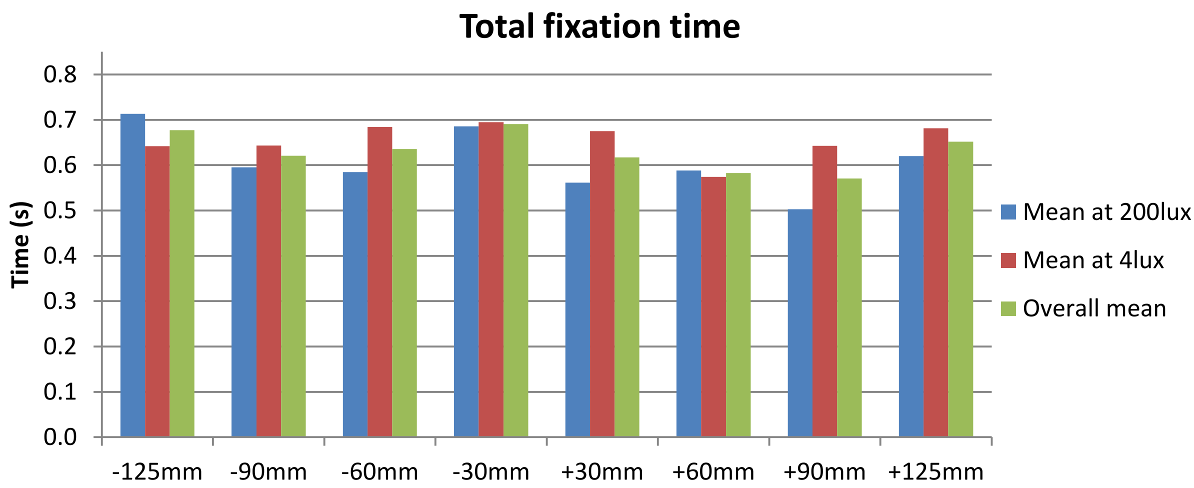


Figure 5-7: The total fixation time for older participants.

The breakdown result of the total fixation time at different lighting levels showed that the Searching Mode might be activated for acquiring more visual information in the lower lighting environment. The total fixation time varied within a comparatively moderate range between step-heights for older participants as opposed to young participant. The finding in Section 5.2.1 was also in line with the distinctive behaviour found in this section. One possible reason for this is that older participants might need up to a certain amount of visual information for planning their gait adjustment regardless of step-heights. The noticeable consistency in the variability of total fixation time could establish older participants' coping strategy to counteract different step-heights in the footway environment.

Trial effect was also found in the total fixation time and Trial 1 was significantly longer than both Trial 2 and Trial 3 (with p = 0.04 and p < 0.001 respectively). The decrease in total fixation time along the trial order suggested a possible trade-off between the visual processing demand and gait adjustment planning, also previously discussed in Section 5.2.1. The coping strategy of making use of the familiarity of the environment might help plan gait adjustments in advance.

5.2.4 Total gaze time

The total gaze time was significantly correlated with lighting level (p = 0.008); however, as opposed to the trend of the effect of lighting level on mean fixation duration and total fixation time, older participants showed a longer gaze time in 200lux than 4lux (p = 0.006) (see Figure 5-8). The finding in the early total gaze time in relation to the time of crossing step-heights provided complementary result that the participants directed their first gaze to step-heights earlier in 200lux than 4lux (see Figure 5-9). The increased availability of visual information in the better lit environment of 200lux as opposed to 4lux might explain the longer total gaze time in 200lux.

In comparison to young participants, older participants started as well as ended the gaze period later at both lighting levels (see Figure 5-9). This could be explained that older participants were slower than young participants at processing all information presented in the footway environment so that older participants started executing their gaze much later. Another possible explanation could be that older participants had degenerated vision which provided a decreased capability in detecting the environment. In spite of a late start (i.e. a later early total gaze time), the total gaze time did not vary noticeably between two age groups, which showed that the time period was not compromised for older participants, but it caused a knock-on effect on the late total gaze time. It suggested that even though older participants might need a similar amount of time to young participants for information coordination, the final fixation was made closer to step-heights, indicating the visual information was still being extracted at a later stage of preparation phase.

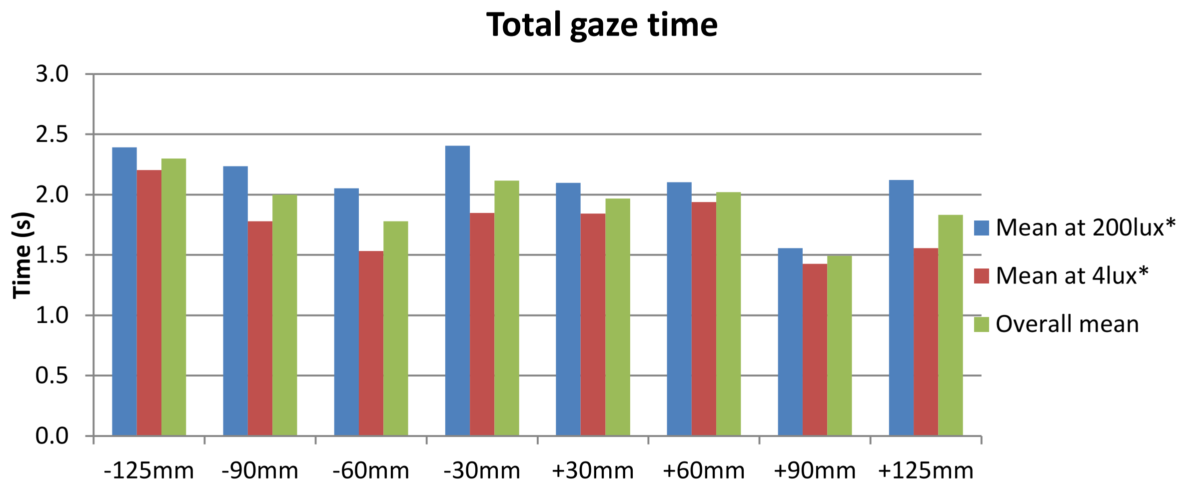


Figure 5-8: The total gaze time for older participants.
* indicates a statistically significant correlation ($p < 0.05$)

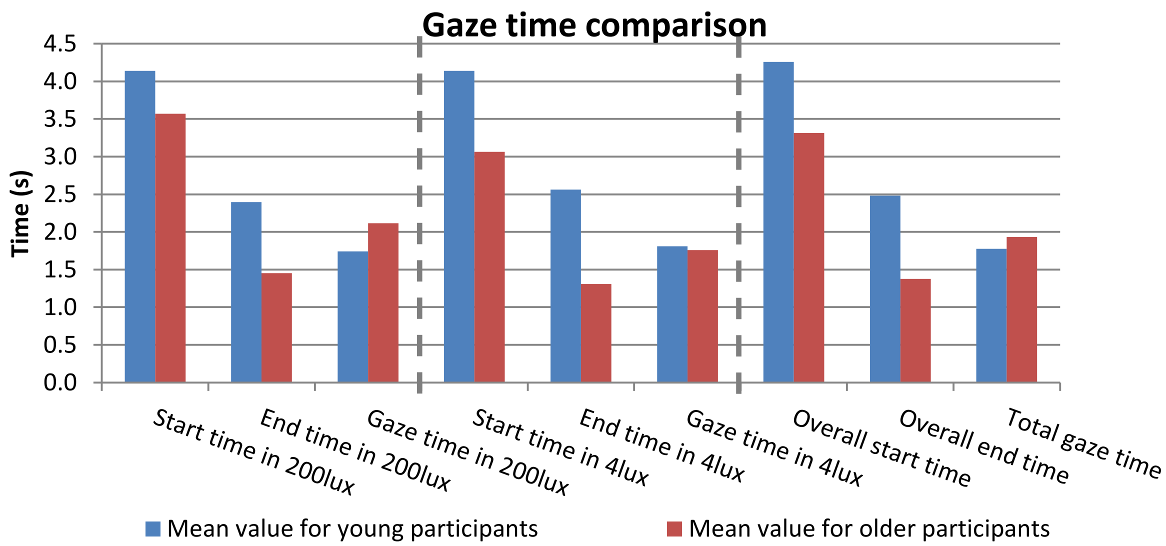


Figure 5-9: Gaze time comparison between young and older age groups.
The start time represents the time period between the occurrence of the first fixation and the passing of step-heights (i.e. early total gaze time). The end time represents the time period between the end of the final fixation and the passing of step-heights (i.e. late total gaze time). The total gaze time was the time period between the start and the end time (i.e. between early total gaze time and late total gaze time).

The lighting level related difference in the mean fixation duration, total fixation time and total gaze time suggested that older participants in the 4lux environment, as opposed to 200lux, took a shorter time period for information coordination for gait adjustments (reflected by shorter total gaze time) but a longer duration for detecting and measuring the step-heights (reflected by the mean fixation duration and the total fixation time). Older participants required more detection time within a shorter coordination period. It suggested that cognitive processing and/or gait adjustments might need to be executed more efficiently in 4lux than in 200lux. Given the inconspicuous visibility of step-heights in 4lux and the decreased gaze time, the 4lux lighting environment seemed to require more visual processing demands as well as cognitive processing and/or gait adjustments, causing further danger to older participants.

Trial effect was found in the total gaze time. Trial 1 was longer than the Trial 2 and Trial 3, especially significantly longer than Trial 3 (p = 0.04). The decrease in gaze time suggested that older participants might gradually learn to coordinate visual information with cognitive processing and/or gait adjustments as trials went. While taking into account the trial effect found in the number of fixations and the total fixation time, older participants seemed to make shorter overall processing as well as coordination time as the trial went, which might suggest the cognitive response and/or gait adjustment were crucial to overcome step-heights so that the time saved could be possibility used for planning and/or implementing coping strategy.

5.2.5 Conclusion of gaze behaviour of older participants

In summary, older participants' gaze behaviour could be interpreted by the six variables analysed in this thesis and the discussion in this section suggested that each step-height could reflect a particular visual perception and imply potential gait adjustments (see Table 5-2). The lighting level was associated with older participants' visual perception and visual coping strategy.

Step-heights of +125 and -125 mm were noticeable and possibly implied that they require more physical capability to be engaged. Step-heights of +60 mm might be perceived as more detectable as well as negotiable whereas +90 might be a threshold of requiring increased physical capability for gait adjustments. Step-heights of -60 and -90 mm, even though being close to mean value of gaze variables, were the most inconspicuous among descending step-heights. Both of the comparatively subtle step-heights of +30 and -30 mm were perceived as potential dangers because of the subtly and ambiguity.

The Searching Mode was activated at 4lux, demanding a longer detection and processing time. However, in the meantime the 4lux lighting level caused decreased coordination and/or implementation time, bringing another danger to older participants who might need to react to the inconspicuous environment within a constrained period of time.

The degenerated cognitive and/or visual functions could possibly delay the first detection of the step-heights and as part of the consequence the final fixation was made closer to the step-heights as opposed to young participants. Therefore the visual information was still being demanded till the late preparation phase.

The overall gaze behaviour of older participants, reflecting part of their gaze coping strategy, was noticeably consistent across different step-heights but affected by lighting level. It indicated that older people might be alert to counteract the deficiency of the availability of visual information about descending step-heights, but however, they were less capable of counteracting the disturbance caused by lighting level. This strategy could explain why the correlation between step-height and gaze behaviour that was observed in the case of the young participants did not occur in that of the older participants, whereas lighting level was a key factor.

Another coping strategy showed that older participants were also alert to the familiarity of the footway environment. They tended to save sensory processing for cognitive processing for strategy implementation once they noticed a familiar setting in the environment.

The overall gaze behaviour suggested that older participants implemented a conservative coping strategy to counteract different step-heights as well as 4lux lighting level to ensure that a certain amount of visual information was acquired; however, 4lux still deteriorated their visual perception of the environment. The familiarity of the footway environment might also help plan as well as implement the strategy efficiently.

Table 5-2: Summary of the gaze behaviour for older participants.

-125 mm	-90 mm	-60 mm	-30 mm	+30 mm	+60 mm	+90 mm	+125 mm
Checking Group	Low-Attention Group	Checking Group	High-Attention Group	Checking Group	Low-Attention Group	Calculating Group	High-Attention Group
Visually noticeable	Visually ambiguous among descending step-heights	Visually ambiguous among descending step-heights	Visually noticeable	Visually noticeable	Detectable and more measurable	Detectable but less measurable	Visually noticeable

1) The gaze behaviour was more clustered as opposed to young participants, indicating older participants might consistently require a certain level of visual information across all step-heights.
2) The mean fixation duration was longer* in 4lux than 200lux. But the coordination time was shorter in 4lux* (represented by the total gaze time). The 4lux environment might be potentially more dangerous than 200lux.
3) Descending step-heights were made more fixations and longer total fixation time than ascending step-height, which might indicate older participants' coping strategy to visually compensate the ambiguity of descending step-heights.
5) The trial effect* showed that older participants' Central Nervous System might utilise this mental map to direct vision as well as cognitive attention to other demands for balance mechanism.
6) Older participants fixated the step-heights till a later stage of preparation phase, along with a later start, as opposed to young participants.

* indicates a statistically significant correlation ($p < 0.05$).

5.3 Discussion on cluster analysis results

Participants with glasses tended to have shorter mean fixation duration. It could be the case that those who wore glasses might have impaired vision impeding their visual function or the glasses obstructed their visual perception or the glasses helped them see better (hence shorter fixation duration was required). Another explanation could be the glasses, either the spectacles or frames, might have interfered the sensing of the eye trackers, reducing the number or duration of fixation. More than half of the older participants had shorter total gaze fixation than younger participants, indicating the older participants might not be able to detect step-heights as early as young participants due to possible degenerated visual functions. In conclusion, the gaze behaviour of older participants might be deteriorated by degenerated visual functions and glasses might obscure or help receiving visual information.

5.4 Conclusion

When discussing the correlation of step-heights with gaze behaviour across two age groups, each step-height could be associated with a distinctive attribute. The step-heights of -125 and +125 mm were perceived to be noticeable and implied that an increase in the physical capability for gait adjustments might be required. The step-heights of -60 and -90 mm were visually ambiguous to detect. The step-height of +60 mm might be the threshold of visual awareness and +90 mm a threshold of physical capability for gait adjustments. The step-heights of -30 and +30 mm affected the visual perception of young participants in different lighting levels but older participants perceived both step-heights as potential dangers.

Young participants implemented a coping strategy to increase total fixation time in 4lux. The ambiguity of availability in visual information about descending step-heights did reduce the number of fixations and total fixation time, indicating a deficiency in visual information. However, the coping strategy implemented was less noticeable than that of the older participants, who had more consistent as well as more distinctive behaviour. Another coping strategy for young participants is to make use the familiarity of the footway, saving time for corresponding cognitive processing and/or gait adjustments.

Older participants took a conservative coping strategy by acquiring a certain consistent level of visual information across different step-heights. While walking in the environment with a deficiency of visual information, such as 4lux lighting level and upcoming descending step-heights, older participants counteracted it by increasing number of fixations as well as fixation duration. However, in comparison to 200 lux, older participants at 4lux executed a longer mean fixation time for visual information processing in a shorter gaze time for coordinating information with cognitive processing and/or gait adjustments. The information processing load seemed to be much in demand at 4lux, which suggested that 4lux might be perceived even more dangerous.

The comparatively later early total gaze time and late total gaze time for older participants might reflect a degenerated visual capability and the demand for visual information while approaching step-heights and till the late stage of preparation phase. The early total gaze time suggested that older participants might have shorter time for cognitive processing and/or gait adjustments as opposed to young participants.

Older participants might rely on, as well as make use of, the familiarity of the footway environment more than young participants. It implied that familiarity might help older participants coordinate as well as implement gait coping strategy with an increased efficiency.

Chapter 6: Results and discussion on gait patterns

The discussion of the statistical analysis results (see Chapter 4) and descriptive analysis of the four temporal gait variables (double support time, stride time, stance time and swing time) are detailed in this chapter.

This section starts with the gait patterns of young participants (Section 6.1), followed by older participants (Section 6.2). The conclusion for the gait patterns of each age group is summarised in each own section. The interaction between gaze behaviour and gait pattern will be detailed in Chapter 7. It is essential to further investigate and recognise the gait pattern in relation to gaze behaviour as well as the gaze behaviour in relation to gait pattern in Chapter 7, along with individual discussions in Chapter 5 and Chapter 6, in order to understand the interaction among *Provided Capabilities* as well as between *Provided Capabilities* and *Required Capabilities*.

6.1 Young participants

In order to have a holistic understanding of the gait pattern, the mean value (Section 6.1.1), standard deviation (Section 6.1.2) and coefficient of variation (Section 6.1.3) of all of the four variables are discussed separately in the following sections. The conclusion of the gait pattern of young participants is then summarised (Section 6.1.4).

6.1.1 Gait patterns by mean value

The overall mean double support time, stride time and stance time were significantly associated with lighting level (p = 0.007, 0.012 and 0.002 respectively) but not step-height (p = 0.874, 0.994 and 1.000 respectively) whereas swing time did not show significant correlation with either lighting level or step-height (p = 0.697 and 0.06 respectively) (see Figure 6-1). In the 4lux lighting environment, the mean double support time, stride time and stance time were longer compared with the 200lux environment (p = 0.007, 0.012 and 0.002 respectively).

The increase in stride time at 4lux mainly (p = 0.012) resulted from the increase in stance time (p = 0.002) as swing time did not show significant difference (p = 0.06). As a consequence, the double support time increased. This gait adjustment showed that participants might reduce their walking speed in the 4lux condition. One could argue that the increased stride time might indicate an increase in step length which took more time than usual between toe-off and heel-strike; however, the comparatively stable swing time suggested that the increase in stride time might be caused by an increased stance time but not by increased time for making a longer step length. The increase in support time and stride time suggested that walking at 4lux may require greater physical capability than walking at 200lux.

The mean double support time for step-height of +60 mm registered a unique pattern with the longest double support time among all step-heights. It could imply that participants' physical capability was affected by +60 mm the most. However, it is unlikely that this was because it was the most considerable height. It is possibly because it could be around the threshold for the physical capability so that participants had to make a longer double support time to cope with it. But it has to be borne in mind that the difference associated with step-heights was subtle without statistical significance (p = 0.847) so that such an inference might be incomplete or incorrect.

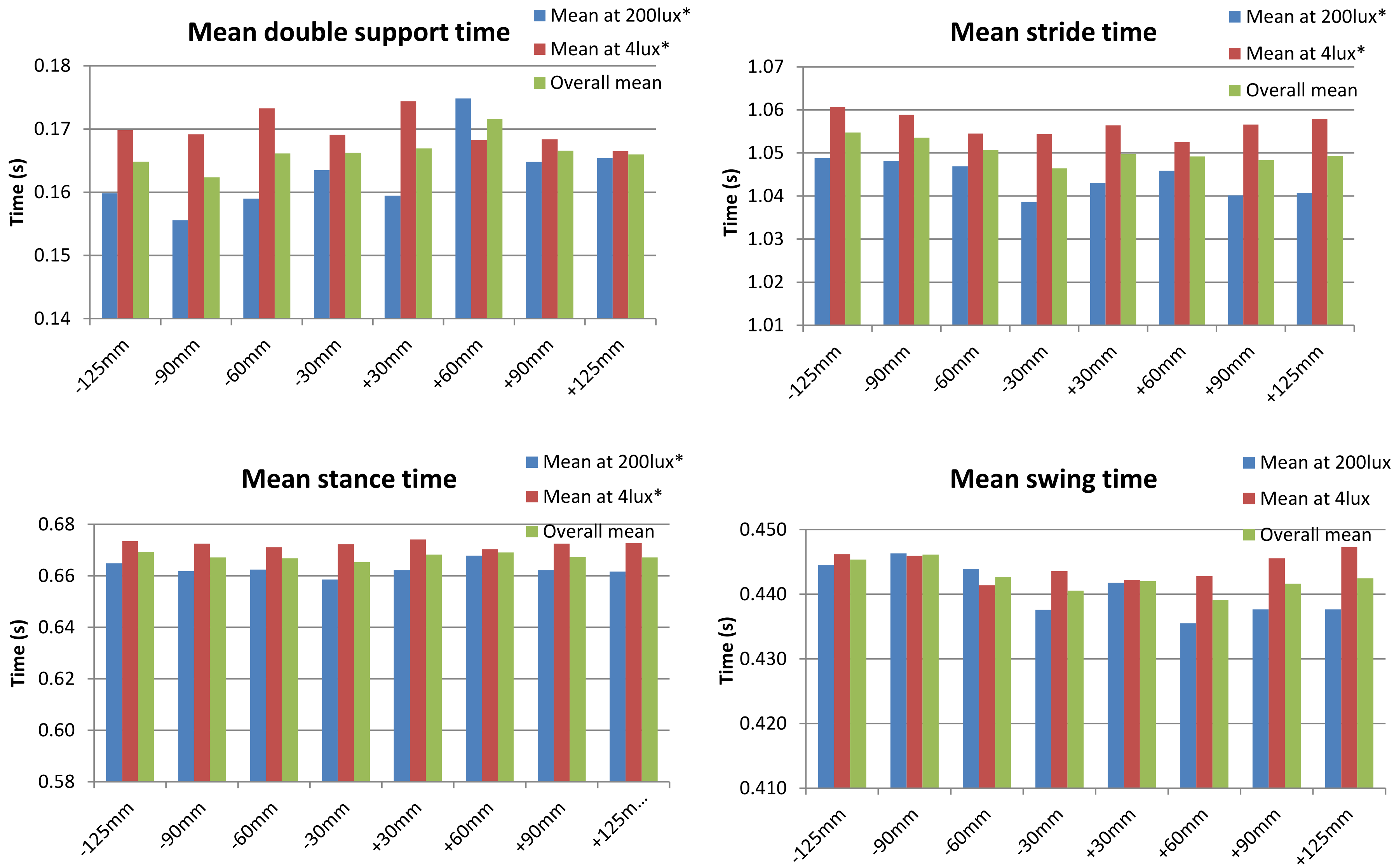


Figure 6-1: Mean value of all gait variables for young participants.
* indicates a statistically significant difference in gait patterns ($p < 0.05$) between lighting levels.

6.1.2 Gait patterns by standard deviation

The standard deviation for double support time was significantly associated with lighting level ($p < 0.001$). The standard deviation for stride time, stance time and swing time, however, were instead associated with step-height (all $p < 0.001$) (see Figure 6-2). The variability for double support time suggested that participants might be more capable of adjusting gait to step-height than lighting level with the synergy between the other three gait variables at a preconscious level. In comparison to ascending step-heights, descending step-heights caused greater disturbance to all gait variables.

The increase in the standard deviation for double support time at 4lux suggests that participants' gait pattern was affected by the lighting level and the 4lux caused greater disturbance to gait adjustment than 200lux. As the consequence, the participants not only had a longer double support time but also a greater variability at 4lux. The increase was noticeable among all descending step-heights. The increase for descending step-heights might be understandable as they may be visually ambiguous which caused further disturbance to gait along with gaze.

Step-heights of +60 and +90 mm had the least standard deviation for double support time at 200lux but the greatest at 4lux. It could be the case that in the environment with natural availability of visual information, such as 200lux, step-heights greater than +60 mm caused a higher level of disturbance. However, at 4lux the step-heights of +60 and +90 mm might be seen as ambiguous (i.e. neither as considerable as +125 mm nor as subtle as +30 mm) and resulted in a greater standard deviation as opposed to 200lux..

The pattern of standard deviation registered in the stride time, stance time and swing time could help explain the adjustment that participants implemented to stabilise the variability of double support time across different step-heights. When comparing the standard deviation for stride time across all step-heights in the ascending order, from -125 to +125 mm, there was a distinctive 'hook' pattern (see standard deviation for stride time in Figure 6-2). The standard deviation was greatest at -125 mm then decreased as the descending height became smaller. When the step-height was raised higher than for the preparation phase, the standard deviation tended to increase slightly. But the degree of increase among ascending step-heights was less noticeable than descending step-height. This pattern suggested that the participants experienced greater disturbances at descending step-heights, particularly for -125 mm (which was significantly greater than the rest of the step-heights apart from -90 mm (with all $p < 0.001$ for the comparison tests between -125mm and -60, -30, +30, +60, +90 and +125mm) and +90 mm (which was significantly greater than 30 mm ($p < 0.001$)). The pattern also suggested that the greater the step-height (regardless of the direction) the greater disturbance that tends to occur.

The 'hook' pattern also appeared in stance time as well as swing time. The variability of standard deviation was greater for descending than ascending step-heights. This variability also became greater for bigger step-heights. The step-heights of -125 mm and -90 mm caused the two greatest amounts of disturbances to the participants.

The pattern of the stride time, stance time and swing time showed that participants made efforts to maintain gait balance by demonstrating a certain period of double support time. This balance strategy was implemented by the synergy of stride time, stance time and swing time.

6.1.3 Gait patterns by coefficient of variation

The pattern for the correlation between step-heights and stride time, stance time as well as swing time was found to be similar to their patterns of the standard deviation. The similarity was understandable as the mean value for each of the four gait variables was stabilised across step-heights. This results in the outcome that the pattern for the coefficient of correlation in each case resembles the associated pattern for standard deviation. The discussion on coefficient of variation could be referred to the discussion on standard deviation in Section 6.1.2.

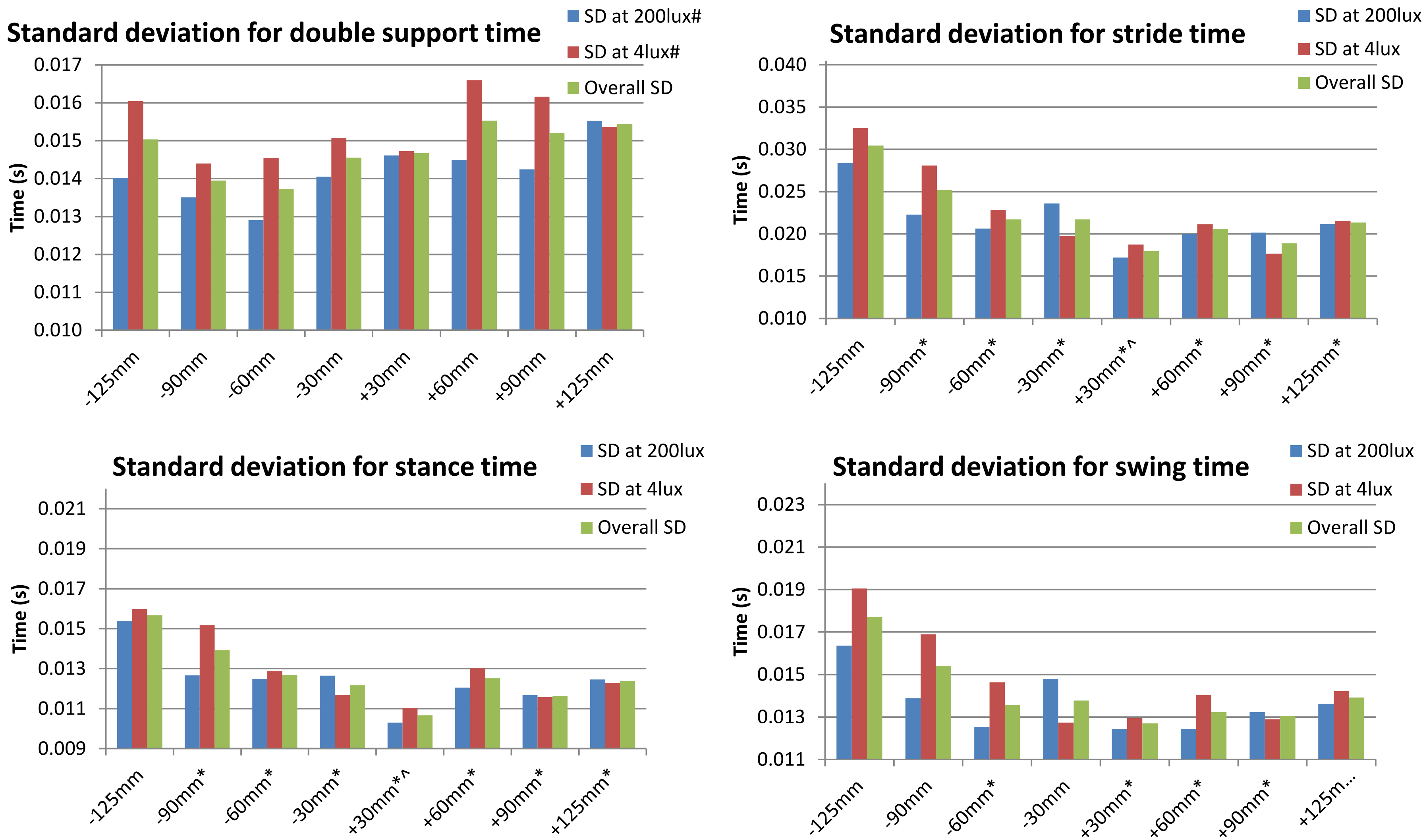


Figure 6-2: Standard deviation of all gait variables for young participants.

# indicates a statistically significant difference in gait patterns ($p < 0.05$) between lighting levels.

* indicates a statistically significant difference in gait patterns ($p < 0.05$) with -125 mm.

^ indicates a statistically significant difference in gait patterns ($p < 0.05$) with -90 mm.

6.1.4 Conclusion on the gait pattern for young participants

The indicator for the balance mechanism, double support time, revealed that young participants were capable of counteracting different step-heights with stabilised time and less noticeable variability than the older participants (see related discussion in Section 6.2). As the double support time did not change noticeably, it indicated that the consistent pattern of double support time may be the result of the synergy between the gait variables of stride time, stance time and swing time. However, the double support time increased in the case of the 4lux condition which might suggest that young participants were trying to increase their stability at 4lux. It is noteworthy that at 200lux, the +60 mm step height demanded the highest double support time, and it might be perceived as a threshold for physical capability, demanding the greatest level of balance mechanism among all step-heights.

The variability of double support time, stride time, stance time and swing time revealed that even though the mean double support time was stabilised across step-heights, greater disturbance was associated with descending step-height, and the greater the height, the more disturbances arose.

6.2 Older participants

In order to have a holistic understanding of the gait pattern, the mean value (Section 6.2.1), standard deviation (Section 6.2.2) and coefficient of variation (Section 6.2.3) of all of the four variables were discussed separately in the following sections. The conclusion of the gait pattern of older participants is then summarised (Section 6.2.4).

6.2.1 Gait patterns by mean value

The mean double support time, stride time and stance time were significantly associated with lighting level (p = 0.007, 0.012 and 0.002 respectively) but not step-height (p = 0.220, 0.945 and 0.692 respectively). Swing time did not show significant correlation with either lighting level or step-height (p = 0.697 and 0.06 respectively) (see Figure 6-3). In the 4lux lighting environment, the mean double support time, stride time and stance time were each longer than they were in the 200lux environment. The increase in double support time was noticeable across all step-heights.

The increase in stride time at 4lux ($p = 0.028$) mainly came from the increase in stance time ($p < 0.001$) as swing time did not show significant difference ($p = 0.902$) and the mean swing time tended to be stabilised across all step-heights. The double support time therefore increased. This gait adjustment showed that participants might slow their walking speed in the 4lux environment. One could argue that the increased stride time might indicate an increase in step length that took more time between toe-off and heel-stride; however, the comparatively stable swing time suggests that the increase in stride time might be caused by an increased stance time but not by an increase in step length. The increase in support time and stride time revealed that walking at 4lux might require greater physical capability than walking at 200lux.

At 200lux the step-height of +60 mm gave rise to a noticeably longer double support time, stride time and stance time than the other step-heights, meaning that participants slowed down the walking speed and in the meantime increased the support time. One possible explanation for this could be that step-height of +60 mm was the most ambiguous step-height among all ascending step-heights even though it is neither the most considerable nor the most subtle height. Step-height of +60 mm could also be the threshold of physical capability for ascending step-heights as participants had to make longer double support time to cope with it. It has to be borne in mind that the difference between +60 mm and other step-heights, although noticeable, is not statistically significant ($p = 0.220$ for the association between mean double support time and of step-heights).

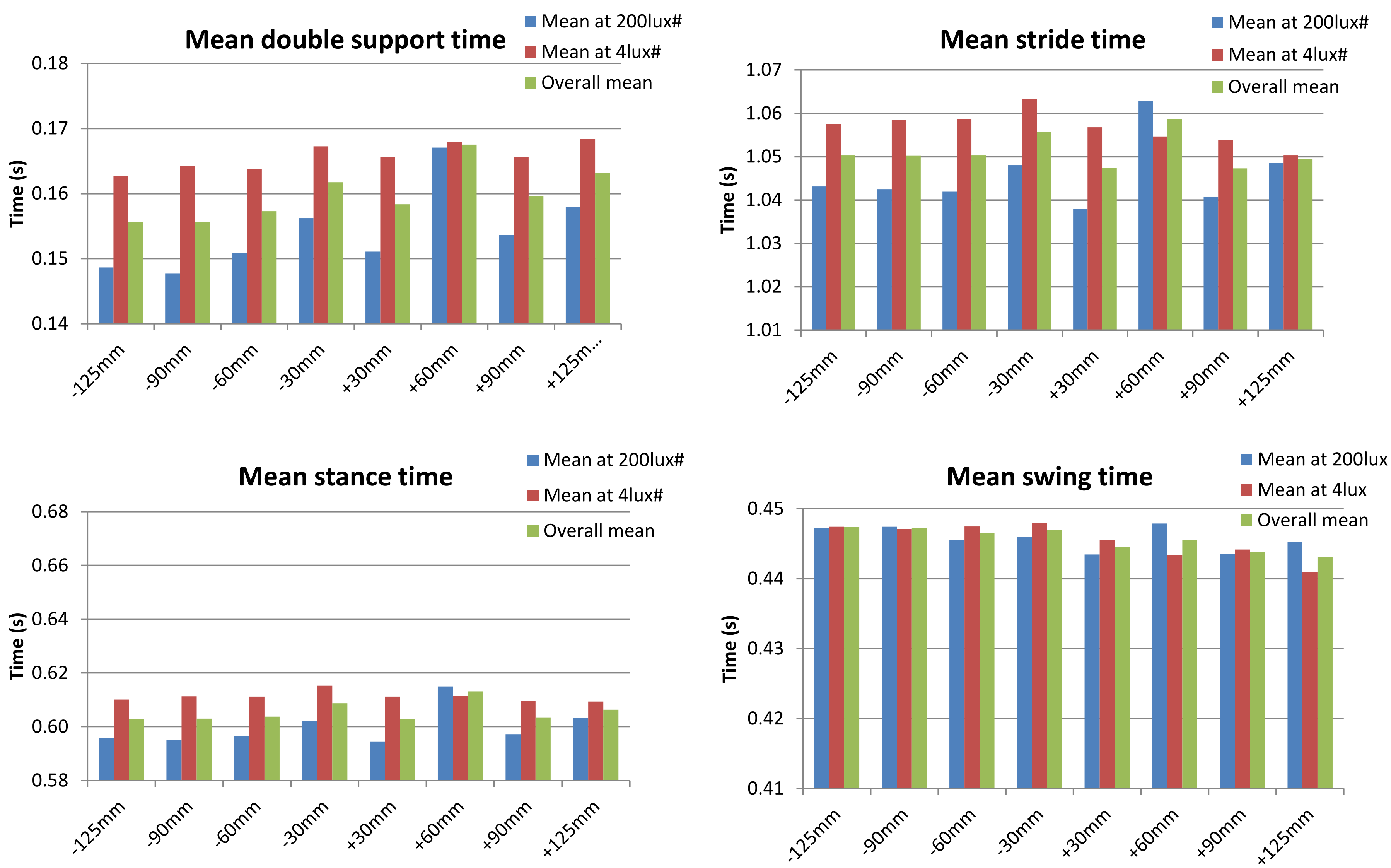


Figure 6-3: Mean value of all gait variables for older participants.

# indicates a statistically significant difference in gait patterns ($p < 0.05$) between lighting levels.

The stance time and double support time were each shorter for the older than the young participants due in part to a reduced number of strides (see Figure 6-4). The increase in number of strides could be explained by a general age-related degeneration of the balance mechanism or poorer awareness of the footway environment as opposed to young participants (see Section 2.2.1.3) so that older participants tended to make more strides to maintain gait stability. Given the stride time did not vary noticeably between the two age groups but older participants tended to have greater number of strides, older participants might take shorter stride lengths, which could further imply a slower walking speed.

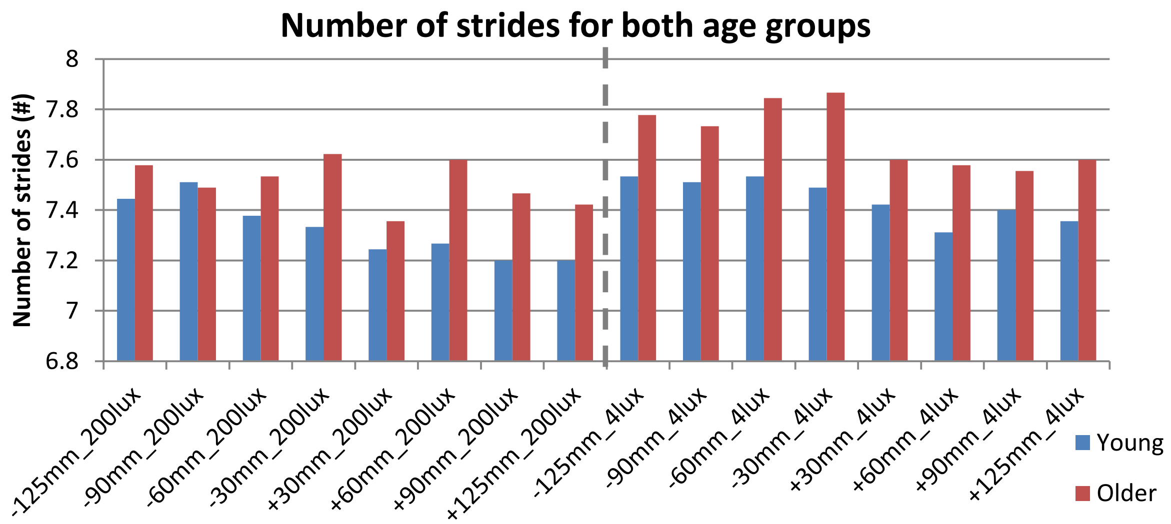


Figure 6-4: Number of strides for both age groups.

6.2.2 Gait patterns by standard deviation

The standard deviation for double support time did not have significant association with environmental factors (p = 0.215 and 0.233 for step-heights and lighting level respectively) whereas the standard deviation for stride time and stance time were correlated to step-height (p = 0.028 and p < 0.001 respectively). The comparative stabilisation for double support time suggested that participants might implement similar gait adjustments at both lighting levels by the synergy between the other three gait variables (see Figure 6-5). In comparison to ascending step-heights, descending step-heights caused greater disturbance to all gait variables.

Despite the fact that the standard deviation of double support time did not have significant correlation with either step-height or lighting level, its pattern still showed a noticeable trend. The step-height of +60 mm had a marked attribute as it had the longest double support time but the smallest standard deviation. This complements the discussion in Section 6.2.1 that +60 mm could be the threshold of physical capability. Participants might be able to sense and react to +60 mm more easily than other step-heights so that the coping strategy of increasing double support could be implemented whereas it was more negotiable or manageable than other step-heights so that the standard deviation was smaller.

The standard deviation for stride time, stance time and swing time was significantly correlated to step-height (with $p < 0.001$, $p = 0.003$ and $p < 0.001$ respectively). When comparing the standard deviation for stride time across all step-heights in ascending order, from -125 to +125 mm, there is a distinctive 'hook' pattern (see standard deviation for stride time in Figure 6-5). The standard deviation was the greatest at -125 mm and decreased as the height became less considerable but increased again after reaching the lowest variability at +60 mm. But the degree of increase among ascending step-heights was less noticeable than descending step-height. The variability for ascending step-heights was comparatively stabilised. This pattern revealed that the participants experienced greater disturbances at descending step-heights, particularly for -125 mm.

The pattern of the stride time, stance time and swing time for older participants showed a similarity to the gait pattern demonstrated by the young participants. The 'hook' pattern demonstrated the additional disturbance caused by the descending step-heights and considerable step-heights. Older participants also made efforts to maintain balance by providing a certain period of double support time. This balance strategy was, however, implemented by the synergy of stride time, stance time and swing time.

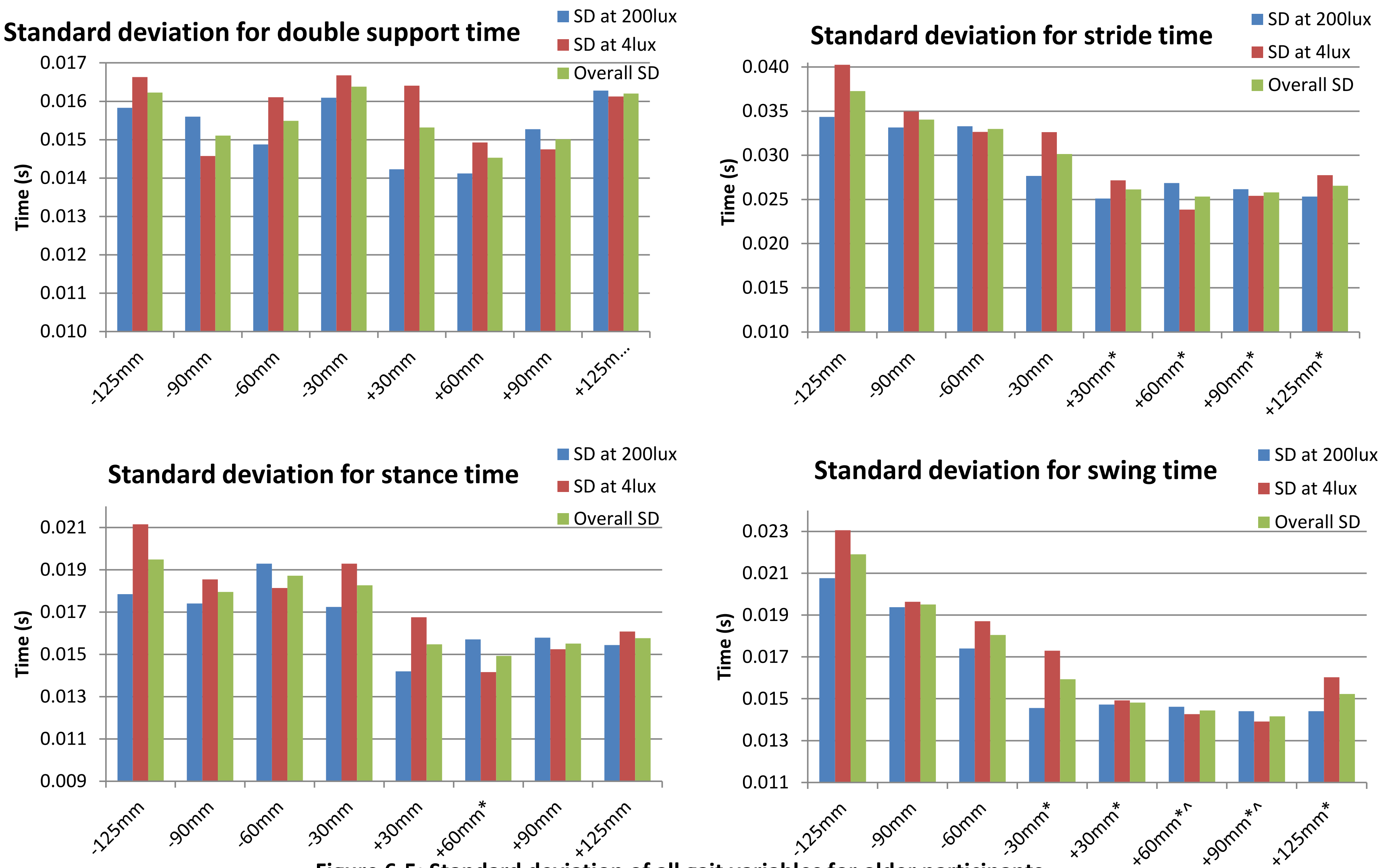


Figure 6-5: Standard deviation of all gait variables for older participants.

* indicates a statistically significant difference in gait patterns ($p < 0.05$) with -125 mm.

^ indicates a statistically significant difference in gait patterns ($p < 0.05$) with -90 mm.

However, there is a difference in gait variability between the two age groups. It is noteworthy that the double support time for older participants had greater variability for descending than ascending step-heights whereas it was the opposite for young participants. The descending step-heights seemed to cause more disturbance to older than young participants. Also in general, the standard deviation was greater for older participants than young participants, indicating that older participants might experience more disturbance than young participants while walking.

6.2.3 Gait patterns by coefficient of variation

The pattern for the correlation between step-heights and stride time, stance time as well as swing time was found to be similar to their patterns of the standard deviation. The similarity was understandable as the mean value of each of the four gait variables was stabilised across step-heights so that the pattern for coefficient of correlation resembles the pattern for standard deviation. The discussion on coefficient of variation could be referred to the discussion on standard deviation in Section 6.2.2.

6.2.4 Conclusion on the gait pattern for older participants

The indicator of balance mechanism, double support time, revealed that older participants were capable of counteracting different step-heights with stabilised time and less noticeable variability. It suggested that the consistent pattern of double support time might be the result of the synergy between the other gait variables. However, the increased double support time at 4lux showed that the gait adjustment was negatively affected by the 4lux lighting level. It is noteworthy that at 200lux, +60mm demanded the longest double support time, and this suggests that it might be perceived as some form of threshold for physical capability, such as lifting the foot to cross the step-height, or a trigger for a different response in the gait adjustment or may be triggered by visual recognition (see Section 2.4.5).

The pattern of the standard deviation for the double support time (see Figure 6-5) showed a similarity in the overall trend (the 'W' pattern) to the gaze behaviour of total fixation time (see Figure 5-7). The most considerable and subtle heights, ±125 mm and ±30 mm, not only required more visual processing demand but also caused greater disturbance to gait stability.

The variability of stride time, stance time and swing time revealed that even though the double support time was stabilised across step-heights, greater disturbance was associated with descending step-height. The more considerable the step-height, the more disturbances the older participants displayed.

Both age groups took a conservative approach in relation to the balance mechanism at 4lux, especially the older participants, for whom the increase in double support time happened across all step-heights. The gait adjustment for both age groups was disturbed by descending step-heights.

The ‘hook’ pattern further revealed increased disturbances from descending step-heights and considerable step-heights in both directions. The step-heights of +60 mm could be the threshold of physical capability or a trigger for a different response in gait adjustment. Overall, the disturbance caused by step-heights was greater for older participants than young participants.

Chapter 7: Results and discussion on the interaction between gaze and gait variables and the implication for footway design

This chapter brings together findings from the gaze behaviour (Chapter 5) and gait pattern results (Chapter 6) in order to understand the interaction between them. Investigating gaze or gait behaviours alone would not be sufficient to understand how footsteps are being adjusted while visual fixations are taking place and vice versa. By combining the two behaviours, more insights could be gained into how environmental factors affect the sensory as well as physical capabilities and how sensory and physical capabilities are associated to one another.

In this chapter, the interaction between gaze behaviour and gait pattern are presented by means of the comparison between gaze and gait variables in different experimental settings (Section 7.1). The association between the first fixation and the change in gait behaviour along with the magnitude of the effect is demonstrated (Section 7.2). Finally, the result from gaze and gait behaviours will be compared with current footway design guidelines (Section 7.3). Both complementary and advisory suggestions will be described.

7.1 Interaction between gaze behaviour and gait pattern

This section links together the discussions on the gaze behaviour in Chapter 5 and gait pattern in Chapter 6. The discussion in the following sections investigates the influence of environmental factors of step-height and lighting level on the *Provided Capability* of gaze behaviour and gait pattern, starting with young participants (Section 7.1.1), older participants (Section 7.1.2) and the results of the cluster analysis (Section 7.1.3).

7.1.1 Young participants

Both the number of fixations in gaze behaviour and the support time in gait pattern increased at 4lux. The number of fixations implies that the Searching Mode (see its definition in Section 5.1.2) was activated possibly due to the deficiency of visual information, and the increased stride time as well as support time at 4lux further suggests that young participants indeed took a conservative coping strategy at 4lux. The inconspicuous descending step-heights were found in both gaze and gait performance to require increased visual attention (represented by number of fixations and total fixation time) as well as balance mechanism (represented by double support time and stance time).

Among the considerable step-heights of $\pm$125 and $\pm$90 mm (see Table 5.1), young participants showed a lower level of gait variability at +90 and +125 mm but the greatest gait variability at -125 mm. The second greatest gait variability happened at -90 mm, which was visually ambiguous as being a descending step-height. This suggests that, even though these considerable heights might exceed young participants' capability of gait adjustment but, due to the better availability of visual information for ascending step-heights as opposed to descending step-heights, +90 and +125 mm caused less disturbance to gait adjustments whereas descending step-heights of -90 and -125 mm caused more disturbance as there was a lack of visual information. Subtle step-heights of -30 and +30 mm did not seem to cause much disturbance even though the visual perception was affected by the lighting level. The finding suggests that however the step-height was perceived by young participants, the descending step-heights induced a higher level of disturbance than ascending step-heights. The level of disturbance increased as the step-height became considerable.

The pattern for the coefficient of variation for double support time (see Figure 6-2) showed a similar trend as the gaze behaviour of total fixation time (see Figure 5-4) found in Section 5.1.3. Among the descending step-heights, the coefficient of variation was the greatest at -125 and -30 mm, whereas for ascending step-heights, the coefficient of variation increased as step-height increased. This suggests that the most considerable step-heights in both directions and the most subtle descending step-heights caused the greatest disturbance. In the meantime, the discussion on the total fixation time in Section 5.1.3 revealed that -125 and -30 mm were perceived as more dangerous among descending step-heights whereas +125 mm among ascending step-heights. The perception of danger might be reflected in the disturbance in gait pattern.

The step-height of +60 mm was suggested to be the threshold of sensory perception and also the threshold of physical capability.

Trial effect was found in total gaze time but not in gait pattern. This finding could further echo the discussion in the gaze behaviour (Section 5.1.4) that young participants were learning to coordinate visual information more efficiently (represented by the total gaze time) with gait adjustments as the experiment proceeded. It suggests that the Central Nervous System might utilise the mental map to direct vision to other demands for balance mechanism (see Section 2.4.4.4).

7.1.2 Older participants

The mean fixation duration and total fixation time in gaze behaviour and the support time in gait pattern all increased at 4lux. The increase in visual processing demand might be the consequence of the ambiguity of visual information in the low lighting environment, and the increased stride time as well as support time reveals that older participants took a conservative coping strategy at 4lux possibly in order to gain more visual information and in the meantime make longer contact with the footway. The conservative strategy was found across all step-heights as opposed to younger participants who implemented a coping strategy mainly in descending step-heights.

In the gaze behaviour, older participants tended to particularly counteract the ambiguity of visual information at 4lux by increasing the fixation duration. However, the gait variability suggests that they were still more disturbed by the 4lux than 200lux lighting level. In the 4lux environment, the decrease in coordination time (represented by the decrease in total gaze time, see Section 5.2.4) might even exacerbate the disturbance to gait adjustment as older participants tended to have increased fixation duration in a decreased coordination time, suggesting that there might be less time left for making foot adjustments. The increased information processing demand and the greater gait variably both happened in a shorter time period at 4lux. It also suggested that older participants were more concerned about (represented by the gaze behaviour) and disturbed (represented by the gait pattern) by the 4lux lighting level.

The variability in stride time, stance time and swing time for ascending step-height was stabilised regardless of the attributes of gaze behaviour (see Table 5-2). This suggests that even though different step-heights were perceived differently, because of the availability of the visual information, the ascending step-heights might provide more visual information to help with gait adjustments and therefore the variability is less disturbed.

The gaze behaviour has revealed that all of the descending step-heights might be visually ambiguous but older participants tended to counteract the ambiguity by increasing the fixation time. This was not observed in young participants. On the other hand, the variability in stride time, stance time and swing time for descending step-heights became greater as the heights became more considerable. It suggests that the visual ambiguity of descending step-heights might disturb the gait adjustment, and the more considerable the descending step-height, the more variability it caused, regardless of older participants' visual coping strategy.

The step-height of +60 mm seemed to be more detectable and possibly negotiable than the other step-heights, and the gait pattern further showed that it had the longest double support time yet the smallest standard deviation. The finding suggests that +60 mm might provide more adequate visual information so that older participants could implement their gait adjustment in advance without much disturbance.

The pattern of the standard deviation for double support time shows a similar trend as the gaze behaviour of total fixation time, the 'W-shaped' pattern described in Section 6.2.4. Among the descending step-heights, the standard deviation is the greatest at -125 and -30 mm, whereas for ascending step-heights, +30 and +125 mm have the greatest standard deviation. It suggests that the most considerable and subtle step-heights caused the greatest disturbance to participants. In the meantime, the discussion on the total fixation time in Section 5.2.3 revealed that step-heights of $\pm$30 and $\pm$125 mm could be perceived as more dangerous than the other step-heights. The perception of danger was reflected in the disturbance in gait pattern.

Trial effect was found in the number of fixations, total fixation time and total gaze time but not in gait pattern. This finding could further echo the discussion in the gaze behaviour (Section 5.2.4) that participants might trade their visual information processing time for cognitive responses and/or gait adjustments. It suggests that the Central Nervous System might utilise the mental map to direct vision to other demands for balance mechanism (see Section 2.4.4.4). The time saved from visual processing could help plan or implement a coping strategy. But unlike young participants who only had trial effect on the coordination time (represented by the total gaze time), older participants even saved the visual information processing time (represented by the total fixation time), along with the coordination time (represented by the total gaze time), indicating that they were more concerned about the gait adjustment than young participants.

Older participants have more clustered visual behaviour but greater gait variability than young participants. It could be the case that young participants might be more capable in adapting their gait to different step-heights regardless of the amount of visual information provided and/or received; however, older participants might need a certain consistent amount of visual information to compensate for their degenerating physical capability in adapting their gait to different step-heights. That is to say, older participants might take precautions to acquire more visual information for implementing a gait coping strategy whereas young participants did not reveal as many precautions but nevertheless seemed to be more capable of dealing with step-heights.

7.1.3 Discussion on cluster analysis results

For the coefficient of variation of stride time, those who wore glasses during the course of the experiment tended to have a greater variability. For the coefficient of variation of stance time and swing time, those who had greater variability were more likely to be older female participants with glasses. It could be the case that people with glasses experienced more disturbance than others due to the deficiency in the information received by the degenerated vision or visual obstruction from glasses, and therefore older females with glasses might experience even more disturbances. However, as the sample size for participants with glasses and older females with glasses was small, it would need further research to establish the correlation.

7.2 Change in gait variables associated with the first fixation

The gait pattern of the preparation phase for each trial was divided into two phases: Phase One consisted of the gait pattern happening between the beginning of the preparation phase and before the occurrence of the first fixation; Phase Two consisted of the gait pattern happening between the beginning of the first fixation and the end of the preparation phase. The difference between the two phases (Phase Two minus Phase One) in gait variables of double support time, stride time, stance time and swing time are detailed for young (Section 7.2.1) and older (Section 7.2.2) participants.

7.2.1 Young participants

Young participants registered a pattern in the change in stride time, stance time and swing time similar to the 'hook' pattern of the standard deviation for stride time (see Figure 6-2 in Section 6.1.2). Step-height of -125 and -90 mm had the greatest increase in stride time and swing time. However, the decrease in double support time suggests that young participants could make a longer step length at -125 and -90 mm after the first fixation. Step-heights of -30 and 30 mm had a shorter step length after the first fixation as the stride time did not have noticeable change but the swing time decreased whilst both stance time and double support time increased. The increase in all four variables at -60 mm suggests that the walking speed seemed to slow down. The step-height of +90 mm had decreased stride time, stance time and swing time but increased double support time, indicating that small steps seemed to be adopted. There was not much difference in gait variables at +60 and +125 mm.

The various degrees of changes in gait variables for different step-heights suggests that either the young participants might be able to adapt to the step-heights and therefore there was not a noticeable trend of gait adjustment after the first fixation or they might be able to sense the environment with other visual functions such as saccade.

Changes in stride time, stance time and swing time for descending step-heights were significantly different from changes for ascending step-heights (with $p < 0.001$, $p = 0.02$ and $p < 0.001$ respectively) and the degree of change for descending step-heights was greater than for ascending step-heights. In general, descending step-heights had positive and greater changes whereas ascending step-heights had subtle or negative changes. It suggests that the disturbance to gait adjustment was greater for descending step-heights than ascending step-heights as young participants tended to make more gait adjustments for descending step-heights with a longer step length.

The lighting level, however, had significant correlation with the change in gait variables of stride time, stance time and swing time (with $p = 0.001$, 0.027 and 0.001 respectively). Results of all four variables increased at 200lux whereas the stride time and swing time decreased at 4ux. It could be the case that young participants tend to make comparatively long step-lengths at 200lux but smaller steps at 4lux. This gait characteristic suggests that in the 4lux lighting environment, young participants might implement a conservative gait coping strategy of shortening the step length after being aware of the step-height.

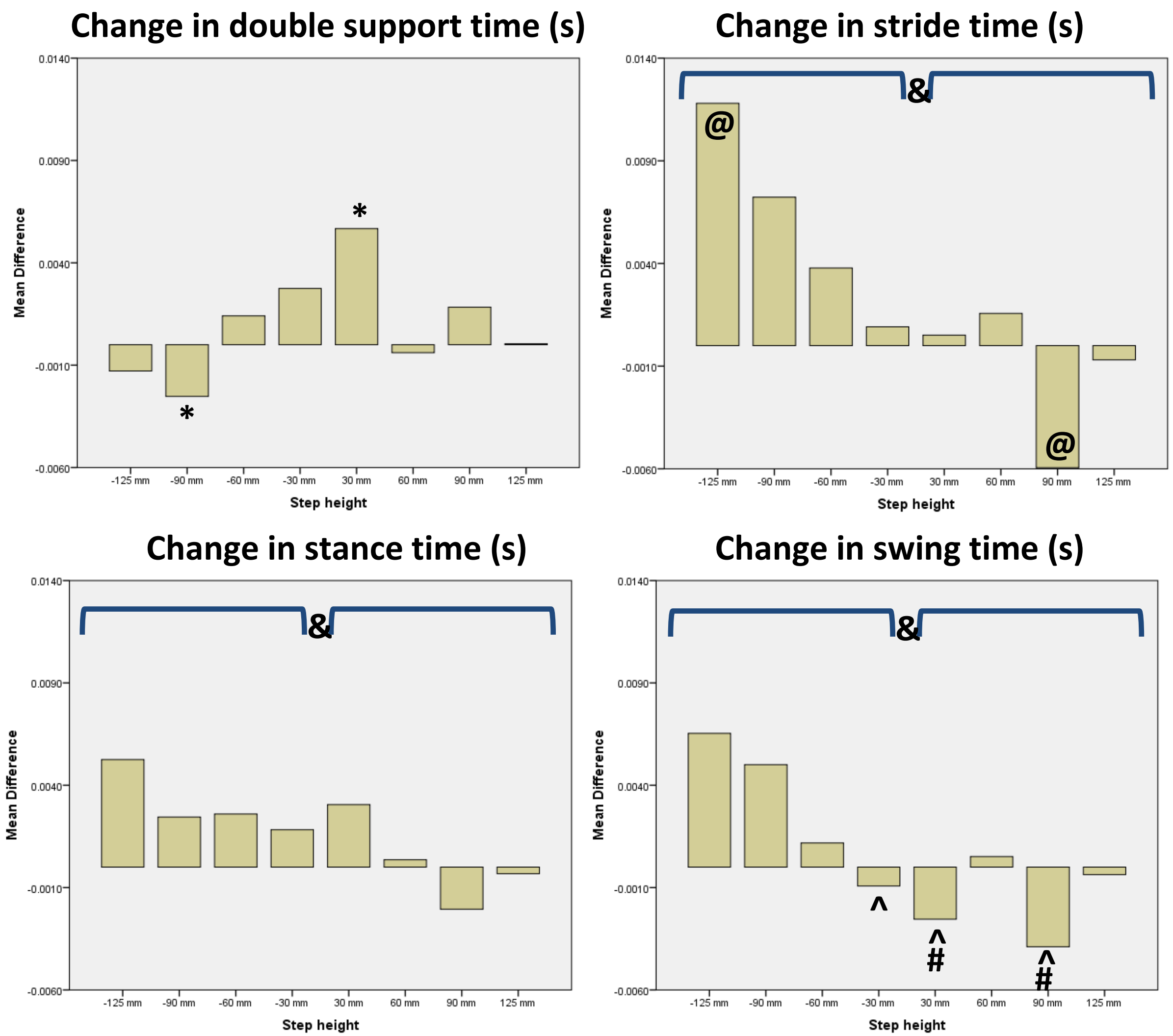


Figure 7-1: Change in gait variables associated with the first fixation (Phase Two minus Phase One) for young participants.

* and @ indicate that there is significant difference with the step-height marked with the same symbol (p < 0.05).
^ indicates significant difference (p < 0.05) with -125 mm.
\# indicates significant difference (p < 0.05) with -90 mm.
& indicates significant difference (p < 0.05) between ascending and descending step-heights.

7.2.2 Older participants

All of the gait variables showed an increase in gait variables from Phase One to Phase Two (see Figure 7-2). In comparison to young participants, the increase for older participants happened across all step-heights. The walking speed for older people seemed to slow down after the first fixation.

The degree of increase in swing time shows that the -90 mm had a noticeable increase that was significantly greater than both +30 and +125 mm. Even though no significant difference in relation to step-heights was found in double support time, stride time and stance time (with p = 0.505, 0.052 and 0.106 respectively), the pattern in swing time could still be explained by these three variables with noticeable patterns. The 'hook' pattern described in the gait variability (Section 6.2.2) was also registered here. Descending step-heights had a significantly greater increase in stride time, stance time and swing time (with p = 0.001, 0.002 and 0.001 respectively) as opposed to ascending step-heights, which had a comparatively stabilised pattern. Step-heights of -125 and -90 mm registered the most distinctive change. This suggests that descending step-heights could require more support time than ascending step-heights after the first fixation, and that the greater descending step-height was the more gait disturbances it caused.

Lighting level was not a significant factor in the change in gait variables (with p = 0.833, 0.235, 0.186 and 0.959 for the change in double support time, stride time, stance time and swing time). Unlike young participants, who had different gait adjustments at different light levels after the first fixation, older participants seemed to respond to different lighting level in a similar way, which could also be seen as more conservative.

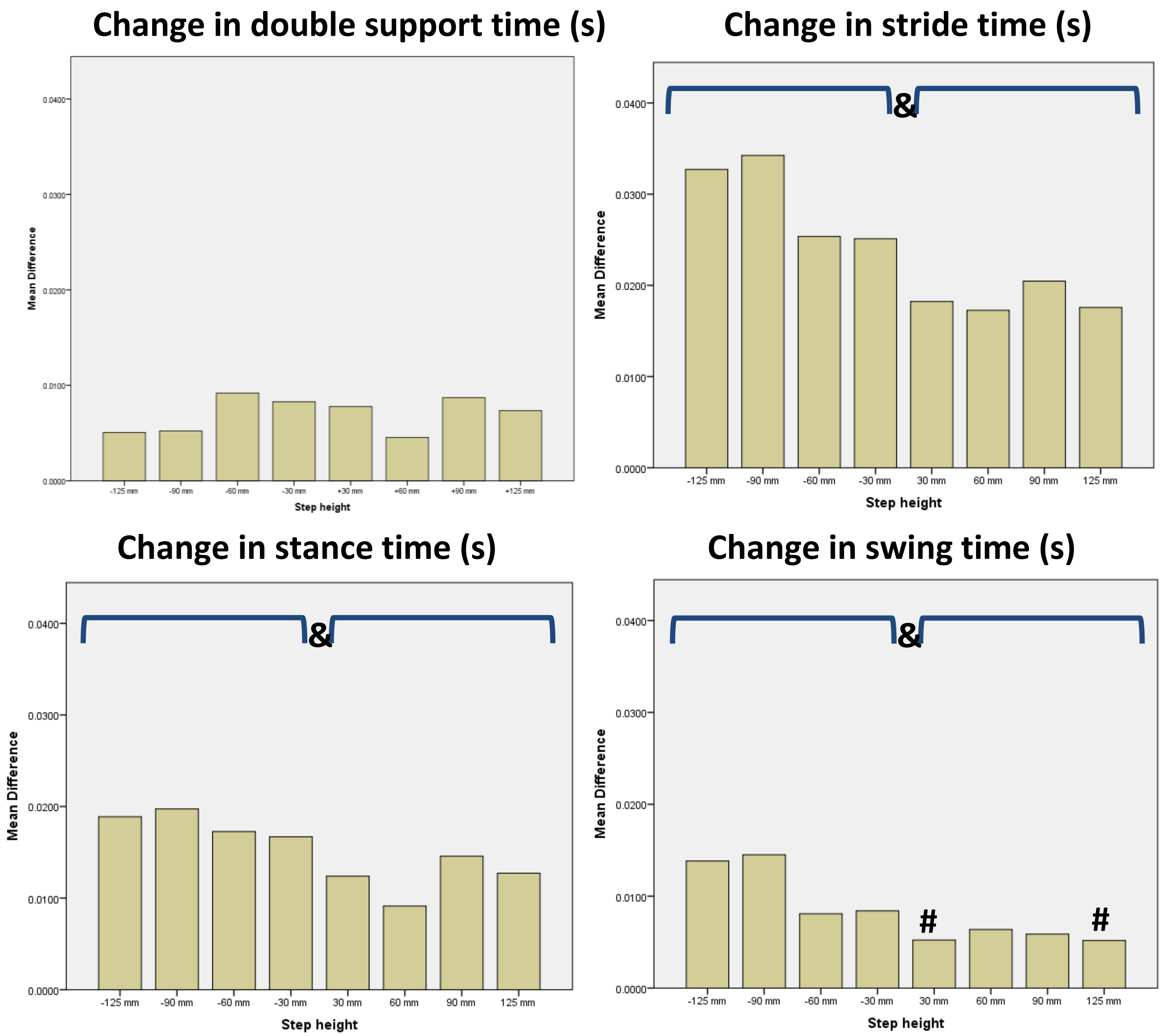


Figure 7-2: Change in gait variables associated with the first fixation (Phase Two minus Phase One) for older participants.

# indicates a noticeable difference ($p < 0.05$) with -90 mm.

& indicates a statistically significant difference ($p < 0.05$) between ascending and descending step-heights.

7.2.3 Discussion on clustering analysis results

Half of the older participants tended to have a greater increase in the stride time and stance time from Phase Two to Phase One. It indicated that older people may be more likely to have greater change in gait pattern after the first visual fixation than young participants. However, due to the small sample size, this finding needs further research to establish the correlation.

7.3 Implication for footway design

Previous research (Campbell, 2005) suggested that in the home environment that people aged at 60 needed three times as much as light as 20-year-olds to navigate around. In addition, the degenerated visual functions provided older people with insufficient capability to sense the streetscape (Lord and Dayhew, 2001). Considering the complexity of elements in the outdoor footway environment, older people might need even more light to navigate in the footway environment and also to compensate for degenerated vision.

This thesis suggests that 4lux, within the suggested range of lighting level for street lighting, caused disturbance to both young and older participants. This thesis also suggests that even though older participants tended to compensate for degenerated vision and/or a lack of visual information at 4lux by increasing the fixation time, the gait pattern still showed a greater variability as opposed to young participants. Compensation in gaze behaviour and greater gait variability for older participants happened more noticeably for descending that ascending step-heights. It showed that older participants might be more visually responsive to ambiguous step-heights in the footway environment but their gait adjustment might still be more disturbed. This thesis suggests that 4lux lighting level might be a potential factor in the risk of falling for both age groups, especially for older participants, and therefore the lighting level should be raised in the outdoor footway environment. Unfortunately there were only two lighting levels investigated in this thesis, so further research is suggested to study the gaze behaviour at a wider range of lighting level.

For both age groups, step-heights of +125 mm caused the greatest disturbance in gait behaviour, followed by -90 mm. The step-height of -125 and +125 mm made the longest fixation time among descending and ascending step-heights respectively. The Inclusive Mobility Guide (Department for Transport, 2005b) suggested a standard kerb height ranging between +125 and +140 mm, which are greater than the step-heights found to be disturbing in this thesis. Therefore the step-height of ±125 mm is not suggested to be designed into footway as it is like to exceed the individual's provided capability, and ±90 might need to be designed with consideration. However, this thesis did not investigate the effect of step-heights between +90 and +125 as well as -90 and -125 mm on participants' sensory and physical capabilities.

The step-heights of -30 and +30 mm also tended to cause comparatively longer fixation time and a greater level of disturbance in gait pattern, especially for older participants. In addition, different lighting levels tended to change the visual perception of -30 and +30 mm for young participants. The finding is in line with the threshold of 30 mm suggested by the UK Pavement Management System (UKPMS) user manual and the hazardous defect threshold of ±30 mm on cobbled pavement indicated in the Westminster Council's Street Standard (Westminster City Council, 2011). The height of ±30 mm was perceived a danger and therefore is suggested to avoid in the footway environment. Also any defect of ±30 mm or greater should be repaired. Previous research suggested other footway defect thresholds, such as ±13 and ±20 mm (Bird et al., 2006; Westminster City Council, 2011); however this thesis did not investigate the effect of step-heights below +30 or above -30 mm on participants' sensory as well as physical capabilities.

Step-heights of +60 mm showed distinctive gaze behaviour as well as gait pattern and could be seen as a threshold of sensory as well as physical capabilities. Any change of level on the footway, such as step and kerb, is suggested to be no greater than ±60 mm to avoid potential risk of falling. A previous study found +40 mm a threshold of tripping because of increased visibility of the defect of +40 mm and above (Murray, 1967). Despite the fact that this thesis did not investigate the step-heights between +30 and +60 mm as well as -30 and -60 mm, this thesis complements the previous study by demonstrating increased gaze behaviour as an indication of increased visibility, which is a proxy for the preconscious response to the step-heights.

This thesis also revealed that participants tended to learn gradually to cope with the footway environment as the experiment proceeded. Therefore participants might be benefitting from the familiarity of the environment and then this improves their process and enables gait adjustments to be better made. Older participants' sensory and/or cognitive responses were found to be associated with the familiarity of the environment. Previous research showed that walking and going up or down changes of level were the two most common activities underway when a fall occurred in older people (Kelsey at el., 2012). In addition, outdoor falls occurred most often at places like the pavement, kerb and street, where different changes in levels are commonly encountered by pedestrians (Li et al., 2006). This thesis echoes previous related studies and suggests that the familiarity of better pavements might help reduce the risk of falling for older people in their daily life.

7.4 Conclusion

This chapter fused the discussions in Chapter 5 and Chapter 6 and tried to find an interaction between gaze and gait behaviour, and the implication of the results for footway design. This chapter has combined the gaze and gait behaviours as the gait pattern could not be explained without the relation to the gaze behaviour, and the gaze behaviour could not be explained in the footway environment without understanding the gait pattern. These two behaviours are inextricably intertwined.

Interaction between gaze and gait

For young participants, the number of fixations increased at 4lux due in part to the deficiency of visual information and both visual attention and balance mechanism were required for descending step-heights due in part to the inconspicuous visibility. Descending step-heights of -90 as well as -125 mm caused the most disturbance to gait stability regardless of the amount of visual information and step-heights of $\pm$30mm did not cause much disturbance despite the fact that lighting levels could affect the visual perception of ±30mm (see Chapter 5 for the discussion on the perception of the subtle step-heights for young participants). Step-height of +60 mm could be the threshold for both visual perception and physical capability. The Trial effect showed that young participants tended to learn to coordinate the visual information and gait adjustments in a familiar environment.

For older participants, a coping strategy of increased mean fixation duration, total fixation time and support time was identified across all step-heights as opposed to young participants who applied this strategy only for descending step-heights. Older participants' coping strategy at 4lux showed that they not only increased the fixation time but also experienced increased disturbance. Descending step-heights were found to be ambiguous as well as disturbing to older participants. Step-heights of ±125 and ±30 mm caused the most disturbances to gait stability. Step-height of +60 mm could be the threshold for both visual perception and physical capability. Trial effect indicated that older people tended not only to learn to coordinate the visual information and gait adjustments but also to save visual information processing time possibly for other cognitive or physical responses.

Change in gait variables associated with the first fixation

The change in gait pattern after the first fixation showed that young participants might be adaptive to different step-heights as the gait pattern had little association with the first fixation. However, 4lux lighting environment might induce smaller and quicker steps than 200lux, which reflected the strategy used to cope with the low lighting level.

For older participants, the walking speed in general slowed down after the first fixation, and the descending step-heights might require more physical capabilities to cope with as opposed to ascending step-heights. However, lighting level had little association with older participants' change in gait variables. For both age groups, descending step-heights tended to cause more disturbances to gait adjustments than ascending step-heights.

Chapter 8: Conclusions

This purpose of this study was to explore the correlation between *Provided Capabilities* (individuals' sensory as well as physical capabilities) and the *Required Capabilities* (environmental factors of step-height and lighting level) using the *Capability Model*, and to compare the results of the correlation with current design guidelines of pavements. This topic was shown as being of importance to understand the condition of the footway environment in relation to pedestrians' ability to plan their coping strategy. The conclusion of this thesis is described by the summary and achievements (Section 8.1), followed by some thoughts about further research in this area that could build on the outcomes of this thesis (Section 8.2)

8.1 Summary and achievement of the thesis

In Chapter 1, the prevalence of falling and the consequences of fall-related injuries were outlined and the vulnerability of older people in the footway environment was explained. The falls incidents among older people were found to be associated with the quality of the footway and, because of the ubiquity of the footway as the means by which people move around outdoors to carry out their daily activities, affect the quality of life in older people. The importance of understanding older people's movement in the footway environment was acknowledged, and the aim and objectives of this thesis were established.

Chapter 2 reviewed the framework of the *Capability Model* used to explain an individual's movement in the footway environment. Within the framework, relevant aspects of each capability as well as activity entailed in the *Capability Model* were detailed. *Provided Capabilities* explored older people's physical, sensory and cognitive capabilities such as gait and posture, vision, vestibular sensation and cognitive function. *Required Capabilities* explored the current pavement design guidance, maintenance manuals and building codes. The interaction between gaze and gait behaviours was explored the physical behaviour performed by the individual when taking part in different walking tasks in different simulated environments.

The review in Chapter 2 revealed that some previous studies focused on task-based performance, such as stepping movements, and some centred on the physical behaviour in static environments. These studies rarely investigated that physical behaviour in dynamic environments and some elements in the footway environment, such as descending step-heights and lighting levels, were not simulated. This leaves a gap in the study of people's interactions with the footway environment: how does a person respond to the changes in the environment which occur on a footway surface, such as a change in level, and how does this affect older people in particular. Using the need to be able to see the change in level as the trigger for being able to respond in terms of a change in control of the feet as an example of such response tactics to an environmental stimulus, this requires the examination of the way in which gaze and gait combine to provide a successful walking activity – or fail to do so, resulting in a stumble, trip or fall. Therefore the research questions in the thesis were set up to investigate the behaviour of gaze and gait performance in relation to different environmental settings of step-height and lighting levels when walking in the simulated footway environment.

Chapter 3 defined the parameters, variables and the capability of measurement in response to the research questions. An experiment was then designed to measure the physical gait behaviour and its relationship to gaze behaviour in the simulated footway environment. The process of the novel instrumentational synchronisation was described along with the follow-up statistical analysis.

Chapter 4 detailed the validation of the instrumentational synchronisation and the outcome of the statistical analysis of the data. Statistical tests investigated the correlation between each gaze or gait variable with each environmental factor along with trial effect for each age group. The change in gait pattern associated with the first visual fixation was also investigated.

Chapter 5 discussed the results of the statistical as well as descriptive tests on the gaze behaviour. Step-heights of -125 and +125 mm were perceived to be noticeable (High-Attention Group) and might require additional physical capability to cross over for both age groups. Step-heights of -90mm and -60mm were visually inconspicuous to detect (Low-Attention or Checking Group). A Step-height of +60mm might be the threshold of visual awareness (Low-Attention or Checking Group) and +90 mm a threshold of physical responses (High-Attention or Calculating Group). For young participants, step-heights of -30 and +30 mm resulted in different visual perceptions at different lighting levels: at -30mm, younger participants seemed not to perceive the height difference at 200lux (Low-Attention Group), whereas at 4lux, the height difference had been perceived (Calculating Group); at +30mm, the result is the opposite. Therefore the direction of step-heights is associated with the visual perception of young participants. However, both step-heights of ±30 mm were perceived as visually noticeable and required attention by older participants (High-Attention and Checking Group).

With regard to the coping strategy, young participants increased total fixation time in the 4lux footway environment, and the ambiguity of descending step-heights is associated with the decrease in gaze variables. For older participants, the level of visual information demanded was consistent compared with young participants. It means however ambiguous or great the step-heights were, older participants demonstrated clustered performance of gaze variables. Within these clustered results, older participants still tended to cope with the 4lux lighting level as well as the descending step-heights by increasing number of fixations and fixation duration. The lighting level of 4lux might even be perceived to be more dangerous for older participants as they needed longer total fixation in a shorter total gaze time for coordinating visual information, to plan footstep and implementing a coping strategy.

Older participants not only started but also ended the gaze time later than younger participants, indicating a possible degeneration in visual capability and/or cognitive processing systems. The step-height detection mechanism for older participants fell behind it for young participants but the total gaze time suggests that once older participants detected, concern was raised about how to cope with the upcoming step-height.

Older participants were also found to be more likely to utilise the trial effect to familiarise themselves with the footway environment than young participants.

Chapter 6 discussed the results of the statistical as well as descriptive tests on the gait pattern. Young participants were capable of stabilising their balance by performing consistent double support time across all step-heights by synergising gait elements of stride time, stance time and swing time, and only the 4lux environment required increased double support time. A step-height of +60 mm at 200lux might be perceived as a threshold for physical capability by registering the longest double support time. Gait variability showed that young participants were able to maintain gait stability but the descending step-heights caused greater disturbance. The more considerable the step-height was, the greater the disturbance that was created.

Older participants were also found to be able to stabilise their gait pattern across all step-heights with the synergy of the other gait elements. The lighting level of 4lux required longer double support time than 200lux. A step-height of +60 mm at 200 lux was also found to be a threshold of sensory as well as physical capabilities. In general, both age groups showed similar gait patterns and demonstrated a longer support time as a conservative coping strategy at 4lux. The descending step-heights caused greater disturbance to both age groups, especially the older group, than the ascending step-heights.

With regard to the gait variability in older participants, the pattern of the standard deviation for double support time was akin to the gaze behaviour of total fixation time. Step-heights of $\pm$125 and $\pm$30 mm, both the greatest and subtlest heights in this thesis, not only required more visual processing demand but also caused greater disturbances to gait stability. In general, the greater the descending step-height, the greater the disturbance it caused.

Chapter 7 discussed the interaction between gaze and gait behaviour and the implication for footway design. This chapter merged the discussions in Chapter 5 and Chapter 6 and tried to find an interaction between gaze and gait behaviours. For young participants, the number of fixations increased at 4lux due in part to the deficiency of visual information and both visual attention and balance mechanism were required for descending step-heights due in part to their inconspicuous visibility. Descending step-heights of -90 as well as -125 mm caused the most disturbances to the gait stability regardless of the amount of visual information but step-heights of ±30 mm did not cause much disturbance despite that fact the lighting levels could affect the visual perception of -30 and +30 mm. A step-height of +60 mm was the threshold for both visual perception and physical capability. The Trial effect showed that young participants tended to learn to coordinate the visual information and gait adjustment in a familiar environment.

With regard to the interaction between gaze and gait behaviours for older participants, a coping strategy of increased mean fixation duration, total fixation time and support time was identified across all step-heights as opposed to young participants who applied this strategy only for descending step-heights. Older participants' coping strategy at 4lux showed that they not only increased the fixation time but also experienced increased disturbance. Descending step-heights were found to be visually ambiguous as well as disturbing to older participants. Step-heights of ±125 and ±30mm caused the most disturbances to gait stability. Step-height of +60 mm might be more detectable as well as negotiable than the others. Trial effect indicated that older people tended not only to learn to coordinate the visual information and gait adjustments but also to save visual information processing time possibly for other cognitive or physical responses.

The change in gait pattern after the first fixation showed that young participants might be adaptive to different step-heights as the gait pattern had little association to the first fixation. However, 4lux lighting environment might induce smaller steps than 200lux, which reflected the strategy used to cope with the low lighting level. For older participants, the walking speed in general slowed down after the first fixation, and the descending step-heights might require more physical capabilities to cope with as opposed to ascending step-heights. However, lighting level had little association with older participants' change in gait variables. For both age groups, descending step-heights tended to cause more disturbances to gait adjustments than ascending step-heights.

This thesis suggested that for pavement design, the kerb height should be no higher than +60 mm and no lower than -60 mm. Step-height of ±90 mm could be considered if the pavement condition has to be compromised but $\pm$125 mm should be avoided. Step-heights or defects greater than $\pm$30 mm should also be avoided or be repaired. A lighting level of 200lux would be sufficient to equip pedestrians with physical capabilities to perceive as well as respond to the step-heights but 4lux would cause hazard to the footway environment. The lighting level for night time should be improved. The quality of the footway is especially essential to older people as walking in the neighbourhood is one of the most common activities for older people and the familiarity of the environment has been demonstrated to be associated to their decision making process while walking.

Bringing together the gaze and gait research is important as well as essential to understand further the cognitive process. One cannot understand the response to the risks of falling without knowing the visual perception because the vision triggers the gait adjustment. In addition, one cannot understand the gait adjustment to the risks of falling without knowing what the visual trigger is.

In conclusion, this thesis found the young participants were more agile to adapt to the footway environment whereas older participants were more likely to be affected by the footway environment. When designing in step-heights and choosing street lighting levels, older people's perception as well as reaction should be taken into consideration for eliminating potential risks of falling.

8.2 Further research

Based on the limits as well as the results of this thesis, further research is needed to investigate the interaction between sensory as well as physical capabilities and the footway environment. Investigations are suggested to carry out for both *Provided Capabilities* (Section 8.2.1) and *Required Capabilities* (Section 8.2.2).

8.2.1 Provided Capabilities

This thesis mainly centres on the temporal gait pattern and gaze on the step-heights. Further investigation could study the spatial or temporal-spatial gait performance in relation to gaze behaviour, such as the actual distance to the step-height in relation to the current visual fixation and the absolute walking speed during each gait or gaze event, so that a complete in-line adjustment of gait pattern in relation to the gaze behaviour could be understood.

Visual fixation on other parts of the pavement while approaching the step-heights, such as on the preparation or recovering phases, could be investigated so that correlation between the visual information of other elements in the footway environment and the gait adjustment could be understood. In addition to visual fixation, other visual functions such as saccade could also be investigate to how people detect the upcoming step-heights, especially descending step-heights, in the first place.

The comparatively late first fixation for older people might suggest that the underlying mechanism of pre-detection (i.e. why do the eyes fixate for the first time?) has failed to pick up the potential problem, so fails to stimulate an associated fixation. This might be a degeneration of the vision system (i.e. the object is not seen) or in the processing system (the object is seen but not processed as a potential problem and thus fails to stimulate an associated fixation). This thesis could not have studied this to see which of these might be the issue, but might have shown up the issue which would be the subject of further research.

Further research could also investigate the cognitive and gait performance of people with different visual conditions. Older people particularly have multiple age-related visual diseases and different type of glasses, such as bi- or multi-focal glasses, are used to help correct vision. The effect of these visual diseases and glasses on walking in the footway environment is still unknown. Given the small sample size of this thesis, the result of clustering analysis does not reveal much significant correlation between the individual's physical characteristics and physical performance in relation to different environmental settings. But the noticeable result suggests that older female participants with glasses might experience more disturbances from environmental factors as opposed to the other participants. An investigation into the effect of environmental factors on older females with glasses should be pursued.

8.2.2 Required Capabilities

This thesis chose eight step-heights and two lighting levels as environmental variables. Further investigation could consider step-heights between 0 and ±30 mm to study the minimum acceptable level of a defect or step-height, and between +30 and +60 mm as well as -30 and -60 mm to explore a more well-defined threshold of pedestrians' sensory and physical capabilities. Lighting levels between 4 and 15 lux (the upper bound of the S classes illuminacne level suggested by the British Standards BS EN 13201 and the European Standard EN 13021-2:2003) could be tested to define a sufficient street lighting level which would reduce the disturbance to visual perception to the minimum.

With regard to the visual information in the footway environment, such visual information of street elements as signage, marks, wayfinding and crowds could be considered to simulate an experimental setting even closer to a real footway. Other environmental settings such as ambient sound simulating urban traffic, different surface types, and other types of unevenness such as wobbly paving could also be included to study the effects of footway environment on pedestrians' perception.

The conclusion of this thesis also suggests further research into the environmental interventions in eliminating the risk of falling. Warning signage and marks are possible interventions to inform older pedestrians of upcoming hazards, but the effective location and dimension of the signage as well as marks need to be investigated.

The findings of this thesis establish the association between visual perception and gait adjustment in relation to the footway environment, however, the process between receiving visual information and making footsteps requires neuro-scientific investigation.

References

Arfken, C.L., Lach, H.W., Birge, S.J. & Miller, J.P. (1994) The prevalence and correlates of fear of falling in elderly persons living in the community. *American Journal of Public Health*. 84 (4), 565–570.

Austin, N., Devine, A., Dick, I., Prince, R., et al. (2007) Fear of falling in older women: a longitudinal study of incidence, persistence, and predictors. *Journal of the American Geriatrics Society*. 55 (10), 1598–1603.

Bath, P.A. & Morgan, K. (1999) Differential risk factor profiles for indoor and outdoor falls in older people living at home in Nottingham, UK. *European Journal of Epidemiology*. 15 (1), 65–73.

Beauchet, O., Dubost, V., Allali, G., Gonthier, R., et al. (2007) 'Faster counting while walking' as a predictor of falls in older adults. *Age and Ageing*. 36 (4), 418–423.

Bergland, A., Pettersen, A.M. & Laake, K. (1998) Falls reported among elderly Norwegians living at home. *Physiotherapy Research International*. 3 (3), 164–174.

Bird, S., Sowerby, C.R. & Atkinson, V.M. (2006) *Development of a Risk Analysis Model for Footways and Cycle Tracks*. [Online]. Available from: http://www.footways.org/data/uploads/PPR171_Development%20of%20a%20Risk%20Analysis%20Model%20for%20Footways%20and%20Cycle%20Tracks.PDF.

Bosse, I., Oberländer, K.D., Savelberg, H.H., Meijer, K., et al. (2012) Dynamic stability control in younger and older adults during stair descent. *Human Movement Science*. 31 (6), 1560–1570.

Boyce, P.R. (1985) Movement under emergency lighting: the effect of illuminance. *Lighting Research and Technology*. 17 (2), 51–71.

British Standards Institution (2012) *Code of practice for the design of road lighting. Lighting of roads and public amenity areas. BS 5489-1:2013*.

British Standards Institution (2003) *Road lighting. Performance requirements. BS EN 13201-2:2003*.

Brouwer, B., Musselman, K. & Culham, E. (2004) Physical function and health status among seniors with and without a fear of falling. *Gerontology*. 50 (3), 135–141.

Burton, E. & Mitchell, L. (2006) *Inclusive Urban Design: Streets For Life*. Architectural Press.

Campbell, S. (2005) *Deteriorating vision, falls and older people: the links*. [Online]. p.43. Available from: http://www.visibility.org.uk/what-we-do/research/Falls-Report.pdf.

Catalfamo, P., Moser, D., Ghoussayni, S. & Ewins, D. (2008) Detection of gait events using an F-Scan in-shoe pressure measurement system. *Gait & Posture*. 28 (3), 420–426.

Cepolina, E.M. & Tyler, N. (2004) Microscopic simulation of pedestrians in accessibility evaluation. *Transportation Planning and Technology*. 27 (3), 145–180.

Chapman, G.J. & Hollands, M.A. (2010) Age-related differences in visual sampling requirements during adaptive locomotion. *Experimental brain research.* 201 (3), 467–478.

Chapman, G.J. & Hollands, M.A. (2006) Evidence for a link between changes to gaze behaviour and risk of falling in older adults during adaptive locomotion. *Gait & Posture*. 24 (3), 288–294.

Chapman, G.J. & Hollands, M.A. (2007) Evidence that older adult fallers prioritise the planning of future stepping actions over the accurate execution of ongoing steps during complex locomotor tasks. *Gait & posture*. 26 (1), 59–67.

Clinical Knowledge Summaries (2012) Falls - risk assessment - Evidence. *Clinical Knowledge Summaries*. [Online]. Available from: http://www.cks.nhs.uk/falls_risk_assessment/evidence/supporting_evidence/up_go_test_and_turn_180o_test# [Accessed: 22 January 2013].

Cohen, H., Heaton, L.G., Congdon, S.L. & Jenkins, H.A. (1996) Changes in Sensory Organization Test Scores with Age. *Age and Ageing*. 25 (1), 39–44.

Darowski, A. (2008) *Falls: The Facts*. 1st edition. OUP Oxford.

Davoudian, N. & Raynham, P. (2012) What do pedestrians look at at night? *Lighting Research and Technology*. 44 (4), 438–448.

Delbaere, K., Close, J.C.T., Mikolaizak, A.S., Sachdev, P.S., et al. (2010) The Falls Efficacy Scale International (FES-I). A comprehensive longitudinal validation study. *Age and Ageing*. 39 (2), 210–216.

Department for Communities and Local Government (2013) *The Building Regulations 2010: Protection from falling, collision and impact*. [Online]. Available from: http://www.planningportal.gov.uk/uploads/br/BR_PDF_AD_K_2013.pdf.

Department for Transport, G.M.H. (2005) *Inclusive mobility*. [Online]. 15 December 2005. Available from: http://www.dft.gov.uk/transportforyou/access/peti/inclusivemobility [Accessed: 8 December 2010].

Department for Transport, G.M.H. (2007) *Manual for Streets*. [Online]. 29 March 2007. Available from: http://www.dft.gov.uk/pgr/sustainable/manforstreets/ [Accessed: 8 December 2010].

Fotios, S. & Cheal, C. (2009) Obstacle detection: A pilot study investigating the effects of lamp type, illuminance and age. *Lighting Research and Technology*. 41 (4), 321–342.

Fotios, S. & Cheal, C. (2012) Using Obstacle Detection to Identify Appropriate Illuminances for Lighting in Residential Roads. *Lighting Research and Technology*. 45 (3), 362–376.

Fotios, S., Yang, B. & Cheal, C. (2013) Effects of outdoor lighting on judgements of emotion and gaze direction. *Lighting Research and Technology*. 0, 1–15.

Fujiyama, T., Childs, C., Boampong, D. & Tyler, N. (2007) *How do elderly pedestrians perceive hazards in the street? - An initial investigation towards development of a pedestrian simulation that incorporates reaction of various pedestrians to environments*. Paper presented to 11th International Conference on Mobility and Transport for Elderly and Disabled People, Montreal, Canada, 21 June 2007.

Gillespie, L.D., Gillespie, W.J., Robertson, M.C., Lamb, S.E., et al. (2003) Interventions for preventing falls in elderly people. *Cochrane database of systematic reviews*.

Halden, D., Jones, P., Wixey, S. & Aldridge, M. (2005) *Measuring Accessibility as Experienced by Different Socially Disadvantaged Groups: Accessibility Analysis Literature Review*. [Online]. Available from: http://home.wmin.ac.uk/transport/download/SAMP_WP3_Accessibility_Modelling.pdf [Accessed: 17 June 2014].

Harley, C., Wilkie, R.M. & Wann, J.P. (2009) Stepping over obstacles: Attention demands and aging. *Gait & Posture*. 29 (3), 428–432.

Hauer, K., Lamb, S.E., Jorstad, E.C., Todd, C., et al. (2006) Systematic review of definitions and methods of measuring falls in randomised controlled fall prevention trials. *Age and Ageing*. 35 (1), 5–10.

Hausdorff, J.M. (2005) Gait variability: methods, modeling and meaning. *Journal of NeuroEngineering and Rehabilitation*. 219.

Hausdorff, J.M., Nelson, M.E., Kaliton, D., Layne, J.E., et al. (2001) Etiology and modification of gait instability in older adults: a randomized controlled trial of exercise. *Journal of Applied Physiology*. 90 (6), 2117–2129.

Help the Aged (2008a) *Falling Short*. [Online]. Available from: http://www.ageuk.org.uk/documents/en-gb/for-professionals/health-and-wellbeing/id7294_falling_short_the_state_of_our_pavements_2008_pro.pdf?dtrk=true.

Help the Aged (2008b) *Falling short. The state of our pavement. An investigation for the national falls awareness day campaign.* [Online]. Available from: http://www.ageuk.org.uk/documents/en-gb/for-professionals/health-and-wellbeing/id7294_falling_short_the_state_of_our_pavements_2008_pro.pdf?dtrk=true.

Help the Aged (2007a) *Preventing Falls*. [Online]. Available from: http://www.ageuk.org.uk/documents/en-gb/for-professionals/health-and-wellbeing/id6910_preventing_falls_2007_pro.pdf?dtrk=true.

Help the Aged (2007b) *Spotlight Report 2007*. [Online]. Available from: http://www.ageuk.org.uk/documents/en-gb/for-professionals/research/spotlight%20report%202007_pro.pdf?dtrk=true.

Hollands, M.A., Marple-Horvat, D.E., Henkes, S. & Rowan, A.K. (1995) Human Eye Movements during Visually Guided Stepping. *Journal of Motor Behavior*. 27 (2), 155–163.

Hollands, M.A., Patla, A.E. & Vickers, J.N. (2002) 'Look where you're going!': gaze behaviour associated with maintaining and changing the direction of locomotion. *Experimental brain research.* 143 (2), 221–230.

Hollands, M.A., Ziavra, N.V. & Bronstein, A.M. (2004) A new paradigm to investigate the roles of head and eye movements in the coordination of whole-body movements. *Experimental Brain Research*. 154 (2), 261–266.

Horak, F.B. (2006) Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? *Age and Ageing*. 35 (2), 7–11.

Howland, J., Lachman, M.E., Peterson, E.W., Cote, J., et al. (1998) Covariates of fear of falling and associated activity curtailment. *The Gerontologist*. 38 (5), 549–555.

Inclusive Design for Getting Outdoors (2007) *I'DGO Design Guides*. [Online]. Available from: http://www.idgo.ac.uk/design_guidance/index.htm.

Keller Chandra, S., Bockisch, C.J., Dietz, V., Hegemann, S.C.A., et al. (2011) Gaze strategies for avoiding obstacles: Differences between young and elderly subjects. *Gait & Posture*. 34 (3), 340–346.

Kelsey, J.L., Berry, S.D., Procter-Gray, E., Quach, L., et al. (2010) Indoor and Outdoor Falls in Older Adults Are Different: The Maintenance of Balance, Independent Living, Intellect, and Zest in the Elderly of Boston Study. *Journal of the American Geriatrics Society*. 58 (11), 2135–2141.

Kelsey, J.L., Procter-Gray, E., Hannan, M.T. & Li, W. (2012) Heterogeneity of Falls Among Older Adults: Implications for Public Health Prevention. *American Journal of Public Health*. 102 (11), 2149–2156.

Ketchen, D.J. & Shook, C.L. (1996) The Application of Cluster Analysis in Strategic Management Research: An Analysis and Critique. *Strategic Management Journal*. 17 (6), 441–458.

Kirtley, C. (2006) *Clinical Gait Analysis: Theory and Practice, 1e*. 1st edition. Churchill Livingstone.

Kressig, R.W., Gregor, R.J., Oliver, A., Waddell, D., et al. (2004) Temporal and spatial features of gait in older adults transitioning to frailty. *Gait & Posture*. 20 (1), 30–35.

Lamb, S.E., Jørstad-Stein, E.C., Hauer, K., Becker, C., et al. (2005) Development of a Common Outcome Data Set for Fall Injury Prevention Trials: The Prevention of Falls Network Europe Consensus. *Journal of the American Geriatrics Society*. 53 (9), 1618–1622.

Lamoth, C.J., van Deudekom, F.J., van Campen, J.P., Appels, B.A., et al. (2011) Gait stability and variability measures show effects of impaired cognition and dual tasking in frail people. *Journal of NeuroEngineering and Rehabilitation*. 8 (1), 2.

Land, M.F. (2006) Eye movements and the control of actions in everyday life. *Progress in Retinal and Eye Research*. 25 (3), 296–324.

Li, W., Keegan, T.H.M., Sternfeld, B., Sidney, S., et al. (2006) Outdoor Falls Among Middle-Aged and Older Adults: A Neglected Public Health Problem. *American Journal of Public Health*. 96 (7), 1192–1200.

Lindqvist, K., Timpka, T. & Schelp, L. (2001) Evaluation of an inter-organizational prevention program against injuries among the elderly in a WHO Safe Community. *Public Health*. 115 (5), 308–316.

Lord, S.R. & Dayhew, J. (2001) Visual risk factors for falls in older people. *Journal of the American Geriatrics Society*. 49 (5), 508–515.

Lord, S.R., Sherrington, C., Menz, H.B. & Close, J.C.T. (2007) *Falls in Older People: Risk Factors and Strategies for Prevention*. Cambridge University Press, Cambridge

Maki, B.E. & McIlroy, W.E. (2006) Control of rapid limb movements for balance recovery: age-related changes and implications for fall prevention. *Age and Ageing*. 35 (2) 12–18.

Manning, D.P. (1983) Deaths and injuries caused by slipping, tripping and falling. *Ergonomics*. 26 (1), 3–9.

Marigold, D.S. & Patla, A.E. (2007) Gaze fixation patterns for negotiating complex ground terrain. *Neuroscience*. 144 (1), 302–313.

Marigold, D.S. & Patla, A.E. (2008) Visual information from the lower visual field is important for walking across multi-surface terrain. *Experimental Brain Research*. 18823–31.

Marigold, D.S., Weerdesteyn, V., Patla, A.E. & Duysens, J. (2006) Keep looking ahead? Re-direction of visual fixation does not always occur during an unpredictable obstacle avoidance task. *Experimental Brain Research*. 17632–42.

Menz, H.B., Lord, S.R. & Fitzpatrick, R.C. (2003) Acceleration patterns of the head and pelvis when walking on level and irregular surfaces. *Gait & Posture*. 18 (1), 35–46.

Mian, O.S., Narici, M.V., Minetti, A.E. & Baltzopoulos, V. (2007) Centre of mass motion during stair negotiation in young and older men. *Gait & Posture*. 26 (3), 463–469.

Miyasike-daSilva, V. (2011) *Role of visual information during stair locomotion*. [Online] Available from: https://uwspace.uwaterloo.ca/handle/10012/5824 [Accessed: 5 May 2014].

Miyasike-daSilva, V., Allard, F. & McIlroy, W.E. (2011) Where do we look when we walk on stairs? Gaze behaviour on stairs, transitions, and handrails. *Experimental Brain Research*. 209 (1), 73–83.

Miyasike-daSilva, V. & McIlroy, W.E. (2012) Does It Really Matter Where You Look When Walking on Stairs? Insights from a Dual-Task Study. *PLoS ONE*. [Online] 7 (9), e44722. Available from: doi:10.1371/journal.pone.0044722 [Accessed: 5 May 2014].

Montgomery, D.C. (2009) *Design and Analysis of Experiments*. John Wiley & Sons, New York.

Loo-Morrey, M. & Jefferies, S. (2003) *Trip Feasibility Study*. Health and Safety Laboratory, Sheffield, UK.

Mueller, M. & Strube, M. (1996) Generalizability of in-shoe peak pressure measures using the F-scan system. *Clinical Biomechanics*. 11 (3), 159–164.

Murray, M.P. (1967) Gait as a total pattern of movement. *American journal of physical medicine*. 46 (1), 290–333.

National Osteoporosis Society (2011) *National Osteoporosis Society 25th anniversary report - A fragile future*. [Online]. Available from: http://www.nos.org.uk/document.doc?id=904.

Nevitt, M.C., Cummings, S.R. & Hudes, E.S. (1991) Risk Factors for Injurious Falls: a Prospective Study. *Journal of Gerontology*. 46 (5), M164–M170.

O'Loughlin, J.L., Boivin, J.F., Robitaille, Y. & Suissa, S. (1994) Falls among the elderly: distinguishing indoor and outdoor risk factors in Canada. *Journal of Epidemiology and Community Health*. 48 (5), 488–489.

Den Otter, A.R., Hoogwerf, M. & Van Der Woude, L.H. (2011) The role of tread fixations in the visual control of stair walking. *Gait & posture*. 34 (2), 169–173.

Patla, A. & Vickers, J. (2003) How far ahead do we look when required to step on specific locations in the travel path during locomotion? *Experimental Brain Research*. 148 (1), 133–138.

Patla, A.E. (1998) How Is Human Gait Controlled by Vision. *Ecological Psychology*. 10 (3-4), 287–302.

Patla, A.E. (1997) Understanding the roles of vision in the control of human locomotion. *Gait & Posture*. 5 (1), 54–69.

Patla, A.E., Adkin, A., Martin, C., Holden, R., et al. (1996) Characteristics of voluntary visual sampling of the environment for safe locomotion over different terrains. *Experimental Brain Research*. 112 (3), 513–522.

Patla, A.E. & Vickers, J.N. (1997a) Where and when do we look as we approach and step over an obstacle in the travel path? *Neuroreport*. 8 (17), 3661–3665.

Patla, A.E. & Vickers, J.N. (1997b) Where and when do we look as we approach and step over an obstacle in the travel path? *Neuroreport*. 8 (17), 3661–3665.

Pavol, M.J., Owings, T.M., Foley, K.T. & Grabiner, M.D. (2001) Mechanisms Leading to a Fall From an Induced Trip in Healthy Older Adults. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*. 56 (7), M428–M437.

Pelli, D.G., Robson, J.G. & J, A.J.W. (1988) The design of a new letter chart for measuring contrast sensitivity. *Clinical Vision Sciences*. 187–199.

Pickett, A. & Gallagher, A. (2010) *The ukpms user manual volumn 2*. [Online]. Available from: http://www.pcis.org.uk/index.php?p=6/12/0/detail,0,644.

Prince, F., Corriveau, H., Hébert, R. & Winter, D.A. (1997) Gait in the elderly. *Gait & Posture*. 5 (2), 128–135.

Raynham, P. (2004) An examination of the fundamentals of road lighting for pedestrians and drivers. *Lighting Research and Technology*. 36 (4), 307–313.

Raynham, P. (2007) *Public Lighting in Cities*. 2007. In: (Proceedings) International Conference Iluminat 2007. : Cluj-Napoca, Romania. (2007).

Raynham, P. (2006) *Public Lighting, How and Why?*. 2006. In: (Proceedings) Lighting Engineering 2006. : Solvania. (2006).

Scheffer, A.C., Schuurmans, M.J., van Dijk, N., van der Hooft, T., et al. (2008) Fear of falling: measurement strategy, prevalence, risk factors and consequences among older persons. *Age and Ageing*. 37 (1), 19 –24.

Sturnieks, D.L., St George, R. & Lord, S.R. (2008) Balance disorders in the elderly. *Neurophysiologie Clinique/Clinical Neurophysiology*. 38 (6), 467–478.

Tyler, N. (In press) *Accessibility and The Bus System: How buses can transform the world.* 2nd edition. London, Thomas Telford.

Tyler, N. (2006) Capabilities and Radicalism: Engineering Accessibility in the 21st century. *Transportation Planning and Technology*. 29 (5), 331–358.

Westminster City Council (2011) *The Street Standard*. [Online]. 2011. City of Westminster. Available from: http://www.westminster.gov.uk/services/transportandstreets/the-street-standard/.

White, J. & Kerridge, J. (2011) *Cracking under Pressure*. [Online]. Available from: http://d3qkb2hv043xyy.cloudfront.net/fileadmin/gdmain/user/News/Documents/CUP_report_combined1.pdf.

Winter, D.A., Patla, A.E., Frank, J.S. & Walt, S.E. (1990) Biomechanical Walking Pattern Changes in the Fit and Healthy Elderly. *Physical Therapy*. 70 (6), 340 –347.

World Health Organization (2007) *WHO Global Report on Falls Prevention in Older Age*. [Online]. Available from: http://www.who.int/ageing/publications/Falls_prevention7March.pdf.

Wurdeman, S.R., Huben, N.B. & Stergiou, N. (2012) Variability of gait is dependent on direction of progression: Implications for active control. *Journal of Biomechanics*. 45 (4), 653–659.

Yardley, L. & Smith, H. (2002) A prospective study of the relationship between feared consequences of falling and avoidance of activity in community-living older people. *The Gerontologist*. 42 (1), 17–23.

Young, W.R. & Hollands, M.A. (2010b) Can tell older adults where to look reduce falls? Evidence for a causal link between inappropriate visual sampling and suboptimal stepping performance. *Experimental brain research*. 204 (1), 103–113.

Zar, J.H. (2010) *Biostatistical analysis*. Prentice-Hall/Pearson, Upper Saddle River, HJ, USA.

Zettel, J.L., Holbeche, A., McIlroy, W.E. & Maki, B.E. (2005) Redirection of gaze and switching of attention during rapid stepping reactions evoked by unpredictable postural perturbation. *Experimental Brain Research*. 165 (3), 392–401.

Zietz, D. & Hollands, M. (2009) Gaze behavior of young and older adults during stair walking. *Journal of motor behavior*. 41 (4), 357–365.

Zietz, D., Johannsen, L. & Hollands, M. (2011) Stepping characteristics and Centre of Mass control during stair descent: Effects of age, fall risk and visual factors. *Gait & Posture*. 4 (2), 279–284.

Zijlstra, G.A.R., van Haastregt, J.C.M., van Eijk, J.T.M., van Rossum, E., et al. (2007) Prevalence and correlates of fear of falling, and associated avoidance of activity in the general population of community-living older people. *Age and Ageing*. 36 (3), 304 –309.