Aalborg Universitet

AALBORG UNIVERSITY
DENMARK

The Perceived Naturalness of Virtual Walking Speeds during WIP Locomotion

Summary and Meta-Analyses

Nilsson, Niels Chr.; Serafin, Stefania; Nordahl, Rolf

Published in:
PsychNology Journal

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Nilsson, N. C., Serafin, S., & Nordahl, R. (2016). The Perceived Naturalness of Virtual Walking Speeds during WIP Locomotion: Summary and Meta-Analyses. *PsychNology Journal*, *14*(1), 7-39. http://www.psychnology.org/File/PNJ14(1)/PSYCHNOLOGY_JOURNAL_14_1_NILSSON.pdf

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy
If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from vbn.aau.dk on: April 17, 2024

The Perceived Naturalness of Virtual Walking Speeds during WIP locomotion: Summary and Meta-Analyses

Niels Christian Nilsson*[1], Stefania Serafin[1] and Rolf Nordahl[1]

[1]Aalborg University
(Denmark)

ABSTRACT

It is well established that individuals tend to underestimate visually presented walking speeds when relying on treadmills for virtual walking. However, prior to the present studies this perceptual distortion had not been observed in relation to Walking-in-Place (WIP) locomotion, and a number of the factors contributing to the perceptual distortion have yet to be identified. In this paper we present a summary of seven of our studies investigating what factors that influence self-motion perception during virtual walking and two meta-analyses of the findings of the seven studies. The studies relate to how gait cycle characteristics, visual display properties, and methodological differences affect speed underestimation during treadmill and WIP locomotion. The studies suggested the following: A significant main effect was found for step frequency; both display and geometric field of view were inversely proportional to the degree of underestimation; varying degrees of peripheral occlusion and increased HMD weight did not yield significant main effects; and the choice of method (i.e., how the speeds were presented) had a significant effect on the upper and lower bounds of what speeds were perceived as natural. All seven studies compared treadmill and WIP locomotion and higher speeds were generally preferred during treadmill walking, but only some studies found a significant effect. Meta-analyses of the differences between the two movement types revealed a significant difference and provided pooled estimates of the magnitude of this difference.

Keywords: *Virtual reality, locomotion, walking-in-place, treadmill, motion perception.*

Paper Received 24/06/2015; received in revised form 12/04/2016; accepted 12/04/2016.

1. Introduction

A major appeal of immersive virtual reality (IVR) is arguably that it enables users to experience a visceral sense of being in a place other than the one where they are physically located. However, a growing body of evidence suggests that perception of virtual environments is prone to distortions; i.e., perceived distances and speeds tend

Cite as:
Nilsson, N. C., Serafin, S. & Nordahl, R. (2016). The Perceived Naturalness of Virtual Walking Speeds During WIP locomotion: Summary and Meta-Analyses. *PsychNology Journal, 14*(1), 7 – 39. Retrieved [month] [day], [year], from www.psychnology.org.

*Corresponding Author:
Niels Christian Nilsson
Aalborg University Copenhagen, A.C. Meyers Vænge 15, 2450 København SV, Denmark
E-mail: ncn@create.aau.dk

to be distorted and recent work suggests that participants may even misperceive time inside IVR (Bruder & Steinicke, 2014). In this paper, we present work pertaining to perceptual distortions of visually presented walking speeds. Particularly, the work deals with the factors influencing underestimations of speeds during virtual walks performed on a treadmill and using Walking-in-Place (WIP) techniques. When relying on WIP techniques the user performs stepping-like movements which serve as a proxy for actual steps. WIP techniques constitute an inexpensive and convenient approach to facilitating relatively natural locomotion through virtual environments when the physical interaction space is limited in size. However, no studies have explored whether walkers underestimate virtual speeds during WIP locomotion as they do when walking on a treadmill, and the factors contributing to the perceptual distortion have yet to be identified. This is important because presentation of perceptually natural walking speeds arguably is a prerequisite for facilitating natural walking experiences on behalf of users navigating virtual worlds using WIP techniques. Moreover, clarification of what factors that influence speed perception during virtual walking may provide valuable insights about human motion perception in general.

It is well established that individuals walking on a treadmill tend to find the visually perceived speed too slow compared to the speed of the treadmill. Banton, Stefanucci, Durgin, Fass, and Proffitt (2005) describe four studies investigating the underestimation of visual speeds during treadmill-mediated IVR. The studies led to the following findings: it was confirmed that geometrically correct optic flow is perceived as too slow; the perceptual distortion may be eliminated if walkers direct their gaze downwards or to the side; the distortion is not affected by step length; and image jitter does not appear to be responsible for the distortion (Banton et al., 2005). Kassler, Feasel, Lewek, Brooks Jr, and Whitton (2010) asked participants to match the speed of projected visuals to the speed of a treadmill by turning a knob. Across six treadmill speeds the results indicated that the participants chose visual speeds that were twice as fast as the treadmill. Notably, the degree of underestimation varies across studies. This may be due to methodological differences (e.g., different visual displays), but it has also been suggested that there may exist a range of different speeds which are perceived as natural at a given treadmill speed (Powell, Stevens, Hand & Simmonds, 2011). In order to investigate this, Powell et al. (2011) performed a study asking participants to differentiate between speeds that were `too slow', `normal', or `too fast' while exposed to two visually distinct virtual hallways and two ways presenting the speeds. No significant differences in the range of perceptually normal gains were found

across the two environments or between the two presentation modes. However, the results suggested that there exists a tolerance in the range of perceptually normal gains. It has been proposed that distortions of visual speeds during virtual walks, at least in part, can be explained by the way in which multi-sensory motion information is processed by the brain. To be exact, Durgin (2009) has proposed that a subtractive model may account for why virtual speeds are perceived as slower by walkers than individuals standing still. Durgin (2009) describe that the perceived speed of the visual flow may be equal to the actual speed of the visual flow minus some amount of the motion information originating within other modalities (e.g., proprioceptive information about limb movement). A reduction in the signal representing visual information may be advantageous because small variations in the speed will seem larger than when compared to the actual speed (Durgin, 2009).

The current paper details a summary of seven of our studies pertaining to self-motion perception during treadmill and WIP locomotion, and two meta-analyses allowing us to draw conclusions that were not possible based on the studies themselves. The first two studies pertain to the influence of gait cycle properties: Study 1 (S1) compared different movement types for virtual locomotion (Nilsson, Serafin, & Nordahl, 2014a), and Study 2 (S2) compared varying step frequencies (Nilsson, Serafin, & Nordahl, 2014b). The following four studies relate to the influence of visual display properties: Study 3 (S3) explored the influence of the display field of view (FOV) (Nilsson et al., 2014a), Study 4 (S4) investigated the effects of geometric mini- and magnification (Nilsson, Serafin, & Nordahl, 2015b), Study 5 (S5) compared different degrees of peripheral occlusion (Nilsson et al., 2015b), and Study 6 (S6) investigated the effects of head-mounted display (HMD) weight (Nilsson, Serafin, & Nordahl, 2015a). The final study investigated the influence of study method; i.e., Study 7 (S7) compared the three different ways of presenting visual speeds to the participants used during S1 to S6 (Nilsson et al., 2015b). All studies compared treadmill and WIP locomotion, but the results are equivocal in regards to the significance and magnitude of the observed difference. Consequently, we present two meta-analyses that help shed light on whether the two movement types lead to different degrees of speed underestimation.

2. User Studies

The seven studies presented throughout the following do, to the best of our knowledge, represent the only existing investigations of how motion is perceived

during WIP locomotion. While each study set out to investigate how different factors influence the perceived naturalness of virtual walking speeds during WIP locomotion, there are a number methodological commonalities.

2.1 Participant Recruitment

All participants were recruited via a mailing list comprising volunteers from Aalborg University Copenhagen and readers of the Danish periodical Ingeniøren (The Engineer). They reported having normal or corrected-to-normal vision and hearing, and they were offered either movie tickets (S1 and S3) or meals as compensation for participating (S2 and S4-S7).

2.2 Task and Environment

In all studies the participants were required to perform a number of walks through a virtual environment using a treadmill and WIP locomotion. During the walks the participants were exposed to a range of visual gains (scalar multiples of their normal walking speeds). With the exception of S1, the participants' normal walking speeds were estimated prior to the first trial by asking them to walk on the treadmill at a step frequency of 1.8 steps per second. The participants then adjusted the treadmill speed until they found a speed they found comfortable. This comfortable speed was used as an estimate of their normal walking speed at 1.8 steps per second, and it was used as the visual speed representing a gain of 1.0. The step frequency of 1.8 steps per second lies just below the one accompanying normal gait speed for both men and women (Öberg, Karsznia, & Öberg, 1993), and it was therefore believed to ensure the safety and comfort of the participants. Throughout all walks, the participants were observed in order to ensure that they did in fact walk at the requested step frequency. During the studies the participants were asked to judge if they found the visually presented speeds to be natural or not. A speed would qualify as natural if the participants, based on their prior experiences of walking, felt that the movement they performed could result in said speed.

In all seven studies the participants were tasked with walking down a virtual corridor. The corridors used for the studies were visually similar but differed in length. The corridor used for S1 and S3 was 14m long whereas the corridor used for S2 and S4-S7 was infinitely long (Figure 1). The participants' real heights were used to determine the vertical position of the virtual viewpoint.

Figure 1. Left: the corridor used for S1 and S3. Right: the corridor used during S2 and S4-S7.

Since gaze direction may influence motion perception (Banton et al., 2005), the participants were instructed to keep their gaze fixed on a painting on the back wall (S1 and S3) or the end of the corridor (S2 and S4-S7).

2.3 Study Stimuli and Setup

The setup was largely identical for all seven studies. The visuals were generated using Unity 3D (www.unity3d.com), and a nVisor SX60 HMD was used deliver the stimuli in all studies except S2. The HMD has a resolution of 1280×1024 and a diagonal FOV of 60° in each eye. The only auditory feedback was the sound of a metronome dictating at what step frequency the participants should walk. The participants head movement was tracked using a 16-camera Optitrack motion capture system (www.optitrack.com). In S2 and S4-S7 a scroll wheel mounted on the right handlebar allowed the participants to control the visual speed. During all conditions, the participants stood on a treadmill (ProForm 520 XLT) and held onto the handlebars during all walks.

2.4 Statistical Analyses

The results of S1, which relied on a single factor design, were analyzed by means of repeated-measures analyzes of variance (ANOVAs). The remaining studies relied on factorial designs, and the results were analyzed using two-way repeated-measures ANOVAs. All ANOVAs were performed using a significance level of $\alpha = .05$. Shapiro-Wilk's test and Mauchly's tests were used to test the assumptions of normality and sphericity, respectively. In case of all studies, significant measures were subjected to post-hoc analyzes using paired-sample, two-tailed t-tests with Bonferroni-corrected alpha values.

3. Gait Cycle Properties

The subtractive model described by Durgin (2009) suggests that perception of walking speeds may be influenced by both external sensory information (e.g, visual motion cues) and internal sensory information, such as proprioceptive and kinesthetic information about limb positions and movements (Waller & Hodgson, 2013). Thus, it seems possible that variations in the movements performed by the walker could influence the perceived naturalness of virtual walking speeds. S1 and S2 investigated the influence of movement type and step frequency, respectively.

3.1 Study 1 (S1): Movement Type

S1 investigated if visual walking speeds are underestimated during WIP locomotion, and if the underestimation is the same across different movement types for virtual locomotion. The study relied on a within-subjects design and compared four different types of user motion: Stationary (the user remained still with both feet on the ground), Tapping-in-Place (TIP) (the user alternately tapped each heel against the ground without breaking contact with the toes), Walking-in-Place (WIP) (the user alternately lifted each foot of the ground), and Treadmill (the user walked on a treadmill).

Methods and Materials for S1

Twenty-two participants (18 males, 4 females) aged between 20-58 years (M= 28.9 years, SD=8.9) took part in the study. The participants performed 22 walks for each condition (11 different gains, repeated twice). The gains ranged from 1.0 to 3.0, in increments of 0.2. Thus, the slowest speed was equal to the estimated normal speed, whereas the highest speed was three times greater. The normal walking speed of the individual participant was derived based on an approach proposed by Wendt, Whitton, and Brooks (2010) as part of their algorithm for Gait-Understanding-Driven Walking-in-Place. This technique takes advantage of the fact that walking speed generally can be expressed as the product of step frequency and step length. Because, step length and height are correlated, the normal walking speed can be estimated based on the height of the walker if the step frequency is known. We established the height of the user during calibration, and all walks were performed at 1.8 steps per second. The metronome dictating the step frequency was also audible during the condition where the participants remained stationary. In a vein similar to Powell et al. (2011), the participants were asked to verbally report if they found the virtual speed of each walk

`too slow', `natural', or `too fast'. The participants made their verdict when they felt confident enough to do so or when the walk was over. Unlike Powell et al. (2011), we chose to randomize the order of the gains in order to prevent the participants from basing their judgements on strategic thinking rather than perception (e.g. by considering the number of walks it took before the first occurrence of perceptually natural stimuli during previous sessions).

Results of S1

For each condition, the lowest and highest gains rated `natural' were identified. The corresponding results are summarized shown in Figure 2. The ANOVA revealed a significant difference between the minimum gains ($F(3, 21) = 3.75$, $p = .02$), but no significance was found maximum gains. The post-hoc analysis ($\alpha = .008$) revealed a significant difference between TIP and Treadmill ($p < .003$). Paired sample t-tests revealed significant differences between all minima and maxima for each movement type and one sample t-tests showed that all minima differed significantly from the normal gain (in all cases $p < .001$).

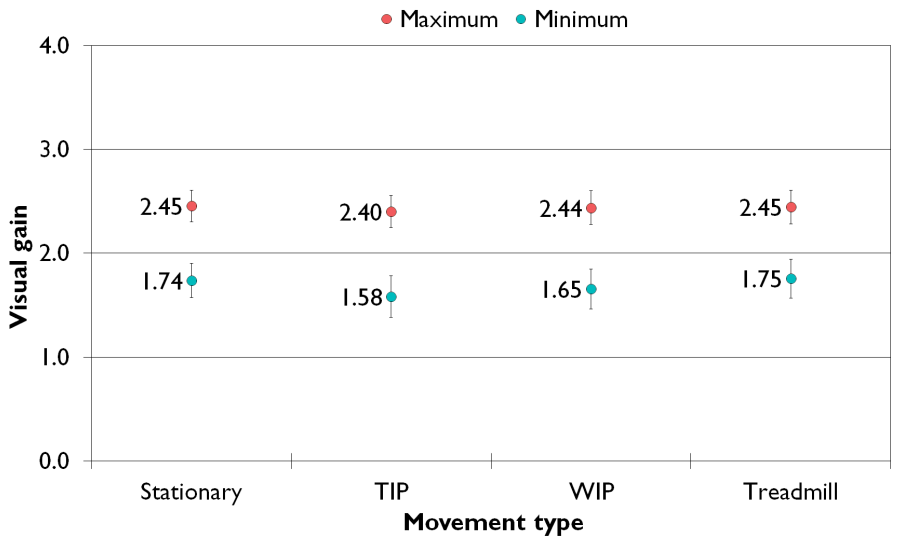


Figure 2. Minimum and maximum visual gains perceived as natural for the four movement types. Error bars indicate 95% confidence intervals.

Discussion of S1

The results pertaining to TIP and WIP suggest that the speed underestimation known from treadmill-mediated virtual walking, also is present when participants are stepping in place. Moreover, the results support the finding that there exist a range of

perceptually natural gains for treadmill walking Powell et al. (2011) and suggest that this also is the case for WIP locomotion.

The results are less conclusive when it comes to the difference between the four movement types. Following the subtractive model described by Durgin (2009) stationary participants ought to find lower speeds natural. The absence of kinesthetic and proprioceptive motion information should entail a lower degree of subtraction, and thus lead to the speeds being perceived as faster, compared to treadmill walking where the subtraction of internal sensory information is present. There is at least one possible explanation for the seeming contradiction between the theory and the current results. Since the step frequency was audible during the stationary condition, we cannot rule out that the metronome tapping served as nonvisual motion information and entailed some degree of subtraction. Moreover, methodological issues may have influenced the results reported for the treadmill condition. Prior to the treadmill condition, the speed of the treadmill was adjusted until the participants were able to walk comfortably in sync with the metronome. The ratio between step length and frequency is normally constant over a large range of walking speeds.

However, this ratio tends to be lower when walking on a treadmill, i.e., shorter and more frequent steps (Durgin, Reed, & Tigue, 2007). This may have produced a mismatch between the treadmill speeds and estimate of the natural walking speed. As for WIP, it is hard to predict whether the degree of subtraction would be higher or lower compared to treadmill walking. On the one hand, the WIP gesture is dissimilar from actual steps, which might lead us to suspect a lower degree of subtraction. On the other hand, studies indicate that walkers tend to find the WIP gesture more physically straining than real walking (Nilsson, Serafin, Laursen, et al., 2013; Nilsson, Serafin, & Nordahl, 2013). If physical effort plays into the subtraction, then one would expect WIP to lead to a higher degree of subtraction and thus lower perceptually natural gains.

3.2 Study 2 (S2): Step Frequency

The objective of S2 was to determine if the range of perceptually natural gains varies across different step frequencies and across treadmill and WIP locomotion. A within-subjects study based on a 2×3 factorial design was performed. The study crossed two movement types (treadmill and WIP) with three step frequencies (1.4, 1.8 and 2.2 steps per second).

Methods and Materials for S2

Nineteen participants (12 males, 7 females), aged between 15-48 years (M = 28.7 years, SD = 8.3), took part in S2. The participants performed 24 walks (4 walks for each of the 2×3 conditions) and were exposed to gains ranging from 0.1 to 4.0. Thus, the slowest speed was a tenth of the estimated normal walking speed while the highest was four times greater. Rather than varying the gains between walks as in S1, the participants were asked to perform a gain-matching task informed by the method of adjustment in a manner similar to the approach used by Kassler et al. (2010). During each walk the participants were able to manipulate the applied gain using a scroll wheel mounted on the right handlebar. The gain was changed in increments of 0.05 with 24 increments per revolution of the wheel. Thus, a full revolution resulted in a gain change of 1.2. While adjusting the speeds, the participants were asked to verbally indicate when the visual speeds reached the lower and upper limits of what felt natural. During two of the four walks per condition, the initial speed was equal to the lowest possible gain (0.1) and during the remaining two it was the highest possible (4.0). Thus, half of the walks required the participants to increase the virtual speed when identifying the lower and upper limit of what speeds they found natural, and the other half required the participants to decrease the speed. A combination of ascending and descending speeds was used so as to minimize errors from habituation and expectations, as it is often done when using the method of adjustment and similar psychophysical methods (Kingdom & Prins, 2010). The order of the four starting speeds per condition was randomized. The order of the conditions with step frequencies of 1.4 and 2.2 was randomized. The condition involving a step frequency 1.8 steps per second was performed as part of S6 which was performed conjointly with S2. The two studies were performed in randomized order. The normal walking speeds at the three step frequencies were established prior to the first trial as described in Section 0.2.2. Finally, it was randomly decided if the initial movement type at each step frequency would be treadmill walking or WIP.

Results of S2

For each condition, the lower and upper bounds of the range of perceptually natural gains (the minima and maxima) were defined as the means of the four lower limits and upper limits, respectively. The results are summarized in Figure 3. In relation to the minima significant main effects were found for both movement type ($F(1, 18) = 16.789$, $p = .001$) and step frequency ($F(2, 36) = 13.589$, $p < .001$), but no significant interaction

was found (*F(2, 36) = 2.413, p = .104*). For treadmill walking the post-hoc tests (*α = .005*) revealed significant differences between the step frequencies of 2.2 and 1.8 (*p < .001*) and between 2.2 and 1.4 (*p < .001*). For WIP significant differences were found between step frequencies of 2.2 and 1.4 (*p = 0.004*). Across treadmill walking and WIP, a significant difference was found between the conditions involving 2.2 steps per second (*p < .001*). Similarly, in regards to the maxima significant main effects were found for movement type (*F(1, 18) = 19.073, p < .001*) and step frequency (*F(2, 36) = 6.443, p = .004*), but no significant interaction was found (*F(2, 36) = 1.355, p = .271*). For treadmill walking the post-hoc analysis (*α = .005*) yielded significant differences between the step frequencies of 2.2 and 1.8 (*p < 0.001*) and between 2.2 and 1.4 (*p = 0.004*) No significant differences were found for WIP. A significant difference was found between the conditions involving 2.2 steps per second across treadmill walking and WIP (p < .001).

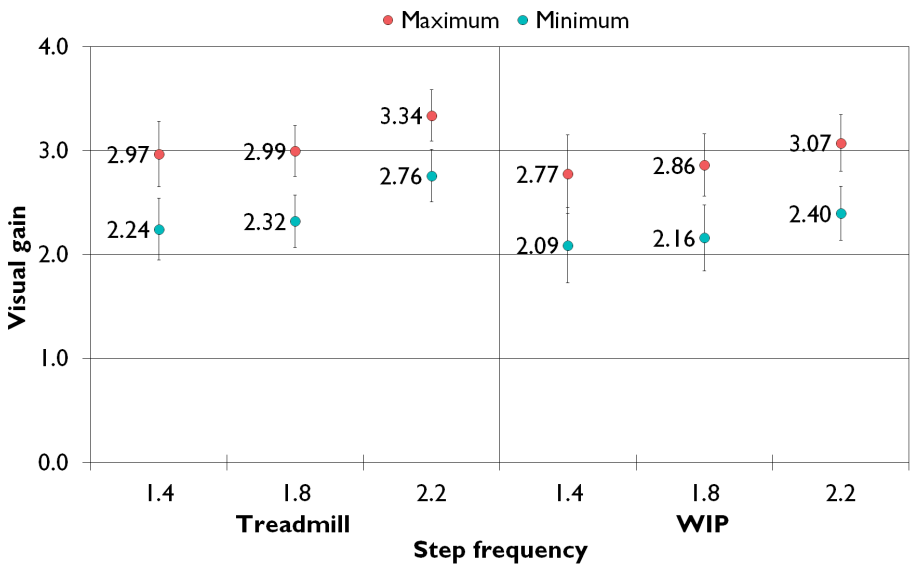


Figure 3. Minimum and maximum visual gains perceived as natural for the three step frequencies across treadmill and WIP. Error bars indicate 95% confidence intervals.

Discussion of S2

With regards to the effects of movement type, the means suggest a notable pattern. Across the board, the means pertaining to treadmill were higher than the corresponding means for WIP. However, the post-hoc analysis only found a significant difference in relation to 2.2 steps per second. It is possible that the lack of significance can be attributed to the limited sample size or the employed method. An increased number of walks per condition combined with alternative psychophysical methods, such as the method of limits or the method of constant stimuli, might have reduced the variability in

the data. However, it we cannot rule out the possibility that the difference between treadmill walking and WIP only is present during high step frequencies.

In relation to step frequency, the means suggest that higher step frequencies may entail a higher degree of underestimation of the visual speed. For treadmill walking significant differences were found between the highest step frequency (2.2 steps per second) and the remaining two (1.4 and 1.8 steps per second) in relation to both minima and maxima, but no difference was found between the two lowest step frequencies. Again, it is possible that the sample size and method are responsible for the lack of significance. Moreover, it is possible that the influence of step frequency is strongest when the frequency is high.

Notably, the three step frequencies used in the current study led to significantly different estimates of the participants' normal walking speeds ($F(2, 36) = 265.85, p < .001$). The step frequencies of 1.4, 1.8, and 2.2 steps per second led to mean speeds of 2.4 ± 0.3, 3.5 ± 0.4, and 4.6 ± 0.5 kmh, respectively. Thus, the current results do not directly correspond with the previous finding suggesting that the same gain may be applicable across six treadmill speeds (Kassler et al., 2010). Possible reasons for the varying results include, variations in the visual display type (HMD and screen-based), the markedly different walking interfaces (a regular treadmill and setup requiring the user to wear a harness), and the high variance in the per participant data in the study by Kassler et al. (2010). Moreover, a study performed by Banton et al. (2005) suggests that the perception of visual speeds is not influenced by stride length. The authors compared two step lengths (normal steps and very short steps) across three treadmill speeds. No main effect of step length was found ($p = .073$), but for the shorter step length the degree of underestimation appears slightly reduced at 3mph and to a lesser extent at 2mph. Since decreasing the step length at a fixed treadmill speed should result in an increased step frequency, these insignificant differences appear to be in line with the current findings.

4. Visual Display Properties

The properties of IVR displays are likely to influence our perception of the virtual environment, including our perception of self-motion. S3 to S6 sought to investigate whether certain display properties affect the perceived naturalness of walking speeds during treadmill and WIP locomotion.

4.1 Study 3 (S3): Display Field of View

Considering that optic flow is central to motion perception, it seems natural that our sensation of speed will be influenced by the extent to which our visual field is occupied by virtual stimuli indicating motion. Particularly, the perceived naturalness of virtual speeds may be influenced by the size of the display field of view (DFOV); i.e., the vertical and horizontal angles subtended by the visual display (Steinicke et al., 2011). Riecke (2010) describes that a primary factor contributing to compelling self-motion illusions is the solid angle subtended by the visual motion stimuli. Even though it has been possible to elicit self-motion illusions with FOV as small as 7.5° (Andersen & Braunstein, 1985), larger FOV generally lead to enhanced illusions, and full-field stimulation may elicit illusions that are so compelling that they become indistinguishable from the real thing (Brandt, Wist, & Dichgans, 1975; Dichgans & Brandt, 1978). To investigate how different DFOV affect natural gain perception, we performed a within-subjects study crossing two movement types (treadmill and WIP) with four viewing conditions (four DFOV sizes).

Methods and Materials for S3

Twenty-one participants (18 males, 3 females) aged between 18-44 years (M= 28.6 years, SD=6.0) took part in the study. The employed method resembled the one used in S1 with the primary difference being the way in which the gains were presented. The participants performed 22 walks (11 different visual gains, repeated twice) for each of the eight conditions (2 movement types × 4 viewing conditions). The normal velocity of each participant was established during a walk on the treadmill prior to the first trial as described in Section 0.2.2. The gain presentation mode was similar to one used by Powell et al. (2011). For each condition, a series of gains was presented, either beginning with the lowest (1.0) or the highest possible gain (3.0). After each walk, the gain would change in increments of 0.2. If the series started with the lowest gain, the gains would gradually increase until the highest gain was reached and then decrease until returning to the lowest gain again. The opposite logic applied if the initial gain was 3.0. It was randomly decided whether the first gain would be 1.0 or 3.0 for each series. As in S1, the participants were asked to report whether they found the visual speed `too slow', `natural', or `too fast'. In order to reduce the risk that the participants relied on strategy rather than perception when making their judgements, we gave them the impression that both the speed of the initial walk and the change in speed between walks might vary. Unlike the remaining studies, S3 used the first Oculus Rift Developer

Kit (henceforth Oculus DK1). This HMD has a resolution of 640×800 (aspect ratio (AR) = 0.8) in each eye and a vertical DFOV of 90°. The four different viewing conditions comprised the unconstrained view of the Oculus DK1 and three constrained views with vertical DFOV of 25°, 50° and 75° (AR = 1.25). The constrained viewing conditions were produced by placing virtual blinders just beyond the near clipping plane of the viewing frustum. Figure 4 illustrates the four viewing conditions. An AR of 1.25 was chosen for the constrained conditions because it is comparable to the one used in HMDs such as the nVisor SX60 and ProView SR80. The orientation of the participants' heads was tracked using the 3DOF sensor embedded within the Oculus DK1. Since this sensor is prone to drift over time, the orientation was reset between each walk.

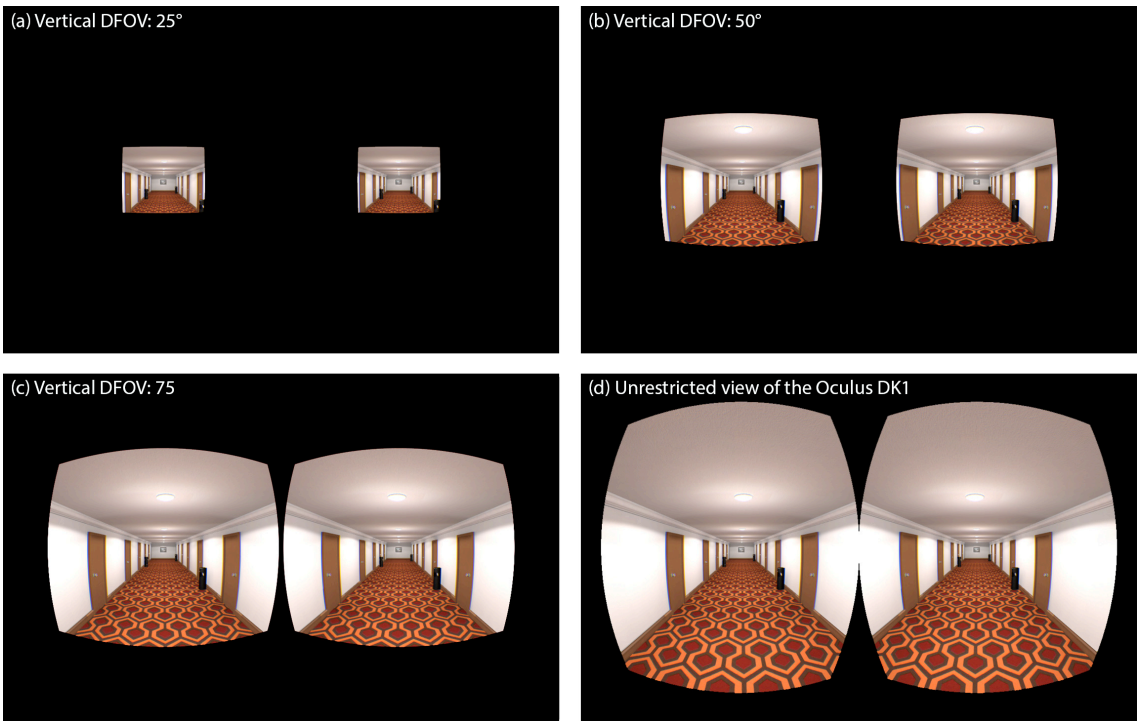


Figure 4. The four viewing conditions used for S3.The distortion constitutes the correction applied for each eye in order to account for the optics of the Oculus DK1.

Results of S3

For each condition the lower bound of the natural speeds (the minimum) was defined as the average value of the two lowest gains rated `natural' (one during the series with ascending gains and one during the series with descending gains). The upper bound (the maximum) was similarly established based on the average of the two highest gains rated `natural'. The corresponding results are summarized in Figure 5. Mauchly's test indicated that the assumption of sphericity had been violated for viewing condition

in relation to minimum gain ($\chi^2(5) = 20.13$, $p < .05$). Thus, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .61$).

In regards to the minima significant main effects were found for DFOV ($F(1.82, 36.41) = 34.21$, $p < .001$) and movement type ($F(1, 20) = 8.26$, $p = .009$), but no significant interaction was found. Similarly, in relation to the maxima significant main effects were found for DFOV ($F(3, 60) = 62.62$, $p < .001$) and movement type ($F(1, 20) = 15.63$, $p < .001$), while no significant interaction was between the two variables was found. Despite the significant main effect of movement type, the post-hoc analysis did not reveal any significant differences in relation to the minimum and maximum gains. However, for DFOV the post-hoc analyzes ($\alpha = .003$) revealed the following significant differences for both minima and maxima: For Treadmill, Oculus DK1 differed significantly from 50° ($p < .001$) and 25° differed significantly from all three viewing conditions. For WIP, Oculus DK1 also differed significantly from 50°, 75° differed significantly from 50°, and 25° differed significantly from the remaining viewing conditions.

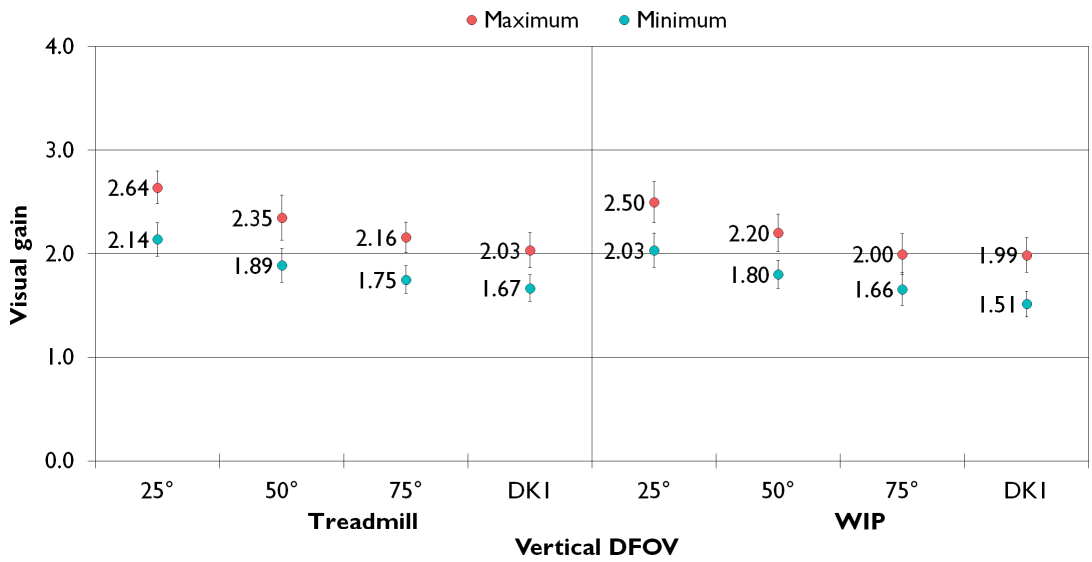


Figure 5. Minimum and maximum visual gains perceived as natural for the four vertical DFOV across treadmill and WIP. Error bars indicate 95% confidence intervals.

Discussion of S3

Significant main effects of movement type were found for both minima and maxima. Despite the lack of significant post-hoc tests, it is worth noting that the upper and lower bounds of the range of perceptually natural gains are slightly higher for treadmill walking than WIP as in S1 and S2. Significant main effects of viewing condition were found in relation to both minimum and maximum, and the post-hoc analysis suggested

that most of the means differed significantly from one another. Judging from the means it would appear that the size of the DFOV is inversely proportional to the degree of underestimation of the virtual speeds for both treadmill and WIP locomotion. However, the differences between the unconstrained view of the Oculus DK1 and the vertical DFOV of 75° were not significant. One interpretation is that the degree to which an increase in DFOV affects speed underestimation diminishes as the FOV becomes larger. Notably, Pretto, Ogier, Bülthoff, and Bresciani (2009) found that seated participants underestimate optic flow speeds, produced using white dots on a dark background, when a circular FOV was smaller than 60° in diameter while no effect was found for larger FOV. That being said, the Oculus DK1 also differed from the remaining conditions in terms of the aspect ratio. Therefore, the varying aspect ratios could have been of influence.

4.2 Study 4 (S4): Geometric Field of View

The geometric field of view (GFOV) describes the virtual counterpart to the DFOV; i.e., the GFOV determines the vertical and horizontal bounds of the virtual viewing volume along with the aspect ratio (Steinicke et al., 2011). In order to ensure an undistorted view of the virtual environment, the GFOV should match the DFOV. If the GFOV is larger than the DFOV, more geometry is forced into the projected image, and this will result in minification. If the GFOV is smaller than the DFOV, the opposite happens. The resulting distortion is referred to as magnification (Steinicke et al., 2011). Even though a match between the GFOV and DFOV is necessary for an undistorted perspective, it has been demonstrated that users wearing a HMD do not always find this undistorted projection to be the most natural. Steinicke et al. (2011) present a study suggesting that some amount of minification may be perceived as more natural than the undistorted view. The size of the DFOV appears to influence what amount of minification will be perceived as natural. Moreover, changes to the GFOV have been shown to influence motion perception during driving simulations (Mourant, Ahmad, Jaeger, & Lin, 2007), and it has been demonstrated that undistorted views tend to cause drivers to underestimate virtual speed (Diels & Parkes, 2010). Thus, it seems reasonable to assume that changes to the GFOV will influence the degree of underestimation experienced during virtual walking. A within-subjects study was performed in order to explore to what extent this is the case. The study was based on a 2×3 factorial design crossing two movement types (treadmill and WIP) with three different vertical GFOV (24°, 34° and 44°).

Methods and Materials for S4

Twenty participants (15 males, 5 females) aged between 15-42 years (M=27.5 years, SD=7.0) took part in S4. This study relied on the same method as S2. The three different degrees of perspective distortion were achieved by manipulating the GFOV. The aspect ratio of the GFOV was kept consistent with the one of the nVisor SX60 (AR = 1.25), but three different vertical GFOV was used: 24° (magnification), 34° (undistorted) and 44° (minification). Figure 6 illustrates the three perspective projections. It was randomly decided if the participants initially were exposed to the three degrees of distortion while walking on the treadmill or while walking in place, and the participants were presented to the three degrees of distortion in randomized order.

Figure 6. The three vertical GFOV used in S4. To make the distortion more easily apparent two virtual objects are highlighted in blue and red.

Results of S4

The minima and maxima were identified as in S2. Figure 7 summarizes corresponding results. Shapiro-Wilk's tests indicated that normality had been violated for the maxima. Nonetheless, two-way repeated-measures ANOVAs were used for analysis of all data since a Friedman's test revealed comparable results in regards to maxima ($\chi^2(5) = 75.382$, $p < .001$). Mauchly's tests indicated that sphericity could not be assumed in relation to the minima for geometric FOV ($\chi^2(2) = 6.6701$, $p < .035$). Thus, degrees of freedom were corrected using Greenhouse-Geisser estimates ($\varepsilon = .76$) A violation was also found for maxima in regards to the interaction between movement type and GFOV ($\chi^2(2) = 9.600$, $p < .008$) and the degrees of freedom were corrected ($\varepsilon = .71$).

No significant interaction was found between the two variables in regards to minima ($F(2, 38) = .814$, $p = .451$) or maxima ($F(1.415, 26.886) = 1.079$, $p = .35$). A significant main effect of GFOV was found for both minima ($F(1.526, 28.989) = 220.252$, $p < .001$) and maxima ($F(2, 38) = 178.356$, $p < .001$). A significant main effect was found for

movement type for minima (*F(1, 19) = 6.207, p = .022*), but not for maxima (*F(1, 19) = 4.180, p = .055*).

The post-hoc analysis of the minima (*α = .005*) revealed significant differences between all three GFOV for both treadmill walking and WIP; i.e., 24° was significantly higher than 34° and 44°, and 34° was significantly higher than 44° (all *p < .001*). The post-hoc tests did not reveal significant differences between the GFOV across the two movement types. Since no significant main effect of movement type was found in regards to maxima, the post-hoc test only compared the three GFOV for either treadmill walking or WIP (*α = .008*). Significant differences were found between all GFOV; i.e., 24° was significantly higher than 34°and 44°, and 34° was significantly higher than 44° (all *p < .001*).

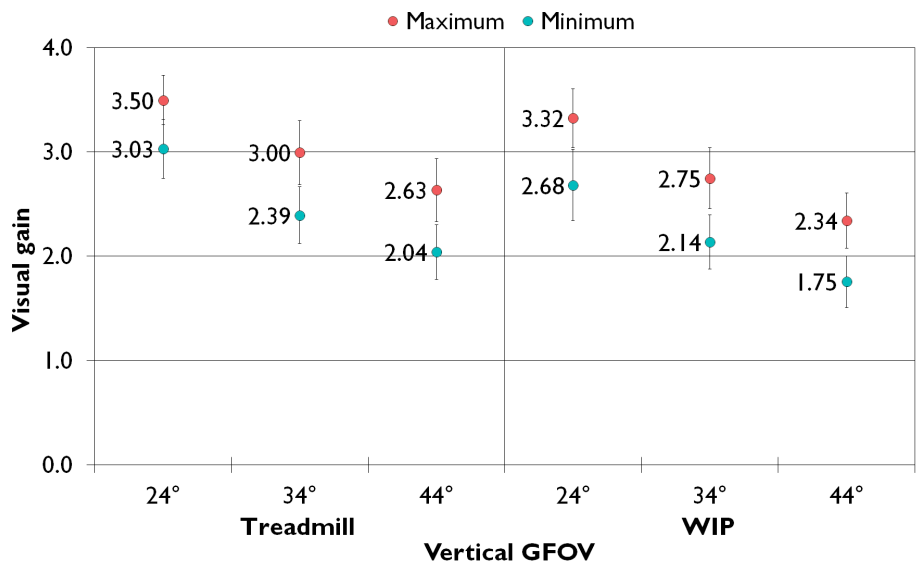


Figure 7. Minimum and maximum visual gains perceived as natural for the three vertical GFOV across treadmill and WIP. Error bars indicate 95% confidence intervals.

Discussion of S4

The identified differences between the three GFOV sizes suggest that GFOV size may be inversely proportional to the degree of speed underestimation in case of both movement types; i.e., speeds closer to the normal walking speed were perceived as more natural for larger GFOV. This finding is consistent with the work pertaining to driving simulations (Diels & Parkes, 2010).

Also, the results appear to be consistent with the finding that some amount of minification is perceived as more natural than an undistorted view of the virtual world (Steinicke et al., 2011). However, the means (Figure 7) suggest that a very large GFOV would be required in order to achieve veridical performance; i.e., it would require an

unnaturally high degree of minification in order for the participants to judge gains of 1.0 to be natural. Finally, a significant main effect of movement type was found for the minima. Despite insignificant post-hoc tests a pattern similar to the preceding studies was apparent; i.e., all means pertaining to treadmill walking were higher than the corresponding means related to WIP.

4.3 Study 5 (S5): Peripheral occlusion

It has been demonstrated that the addition of a static white light in the far periphery of a HMD may positively influence performance on distance judgment and visual scale tasks (Jones, Swan, Edward, & Bolas, 2013). Consequently, it seems conceivable that external peripheral stimulation may affect motion perception during virtual walks. S5 investigated the effects of peripheral occlusion on the perceived naturalness of virtual walking speeds. The study relied on a within-subject, 2×3 factorial design and crossed two movement types (treadmill and WIP) with three degrees of peripheral occlusion (no occlusion, the standard nVisor SX60 blinders and complete deprivation from peripheral visual information).

Methods and Materials for S5

The 20 people who participated in S4 also took part in S5. The participants were exposed to the two studies in randomized order. This study relied on the same method as S2 and S4. The three degrees of peripheral occlusion were achieved by removing the standard blinders from the nVisor SX60, leaving the HMD untouched, and by including the blinders while covering the participants head in a thick cloth shroud (Figure 8).

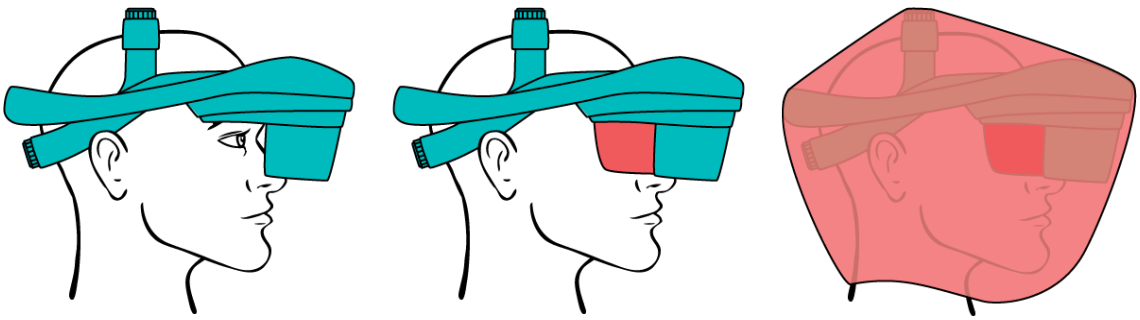


Figure 8. From the left: The nVisor SX60 without blinders, with blinders and with the shroud preventing peripheral stimulation.

Results of S5

The minima and maxima were identified as in S2 and S4. Figure 9 summarizes corresponding results. No significant interactions were found between movement type and peripheral occlusion for minima ($F(2, 38) = 1.274$, $p = .291$) or maxima ($F(2, 38) = .860$, $p = .431$). Also, no significant main effect was found for peripheral stimulation in regards to minima ($F(2, 38) = .221$, $p = .803$) or maxima ($F(2, 38) = 1.097$, $p = .344$). The main effects of movement type were nearly significant for minima ($F(1, 19) = 4.118$, $p = .057$) and maxima ($F(1, 19) = 4.313$, $p = .052$).

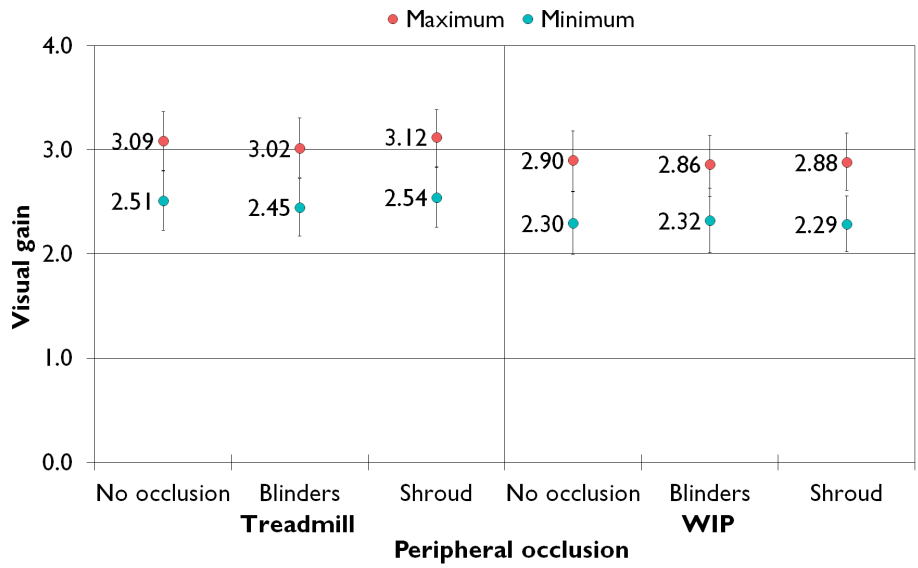


Figure 9. Minimum and maximum visual gains perceived as natural for the three degrees of peripheral occlusion across treadmill and WIP. Error bars indicate 95% confidence intervals.

Discussion of S5

The means (Figure 9) combined with the absence of significant main effects does not support the assumption that peripheral occlusion might influence what speeds the participants experienced as natural. With that being said, it cannot be ruled out that the effect simply was so subtle that the current study failed to identify it. While no significant main effect was found, the results pertaining to movement type, showed the same pattern as the previous studies; i.e., the means pertaining to treadmill walking were generally higher that then ones pertaining to WIP locomotion.

4.4 Study 6 (S6): HMD weight

Willemsen, Colton, Creem-Regehr, and Thompson (2004) performed a study suggesting that the mass and moments of inertia of HMDs may contribute distance underestimations within IVR, even though these display properties cannot fully account

for the perceptual distortion. Moreover, work by Proffitt, Stefanucci, Banton, and Epstein (2003) demonstrated that perception of space may be influenced by locomotor effort. Thus, it was regarded as interesting to explore if whether variations in HMD weight influence perception of self-motion. We performed a within-subjects study based on a 2×2 factorial design crossing two movement types (treadmill and WIP) with two HMD weights (the nVisor SX60 and an altered version which was twice as heavy).

Methods and Materials for S6

The same nineteen participants who took part in S2 also participated in S6. The participants were exposed to the two studies in randomized order. This study relied on the same method as S2, S4 and S5. The HMD weight was manipulated using two versions of the nVisor SX60; i.e., the original display (1050g) and a version with added weights (2050g). Figure 10 illustrates the two versions of the HMD.

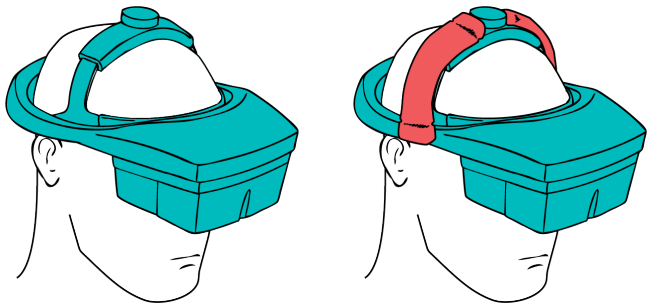


Figure 10. The unaltered nVisor SX60 and the version with two 500g sandbags (red highlights) mounted on the display.

Results of S6

The minima and maxima were identified as in S2, S4 and S5.The corresponding results are presented in Figure 11. In relation to minima, a significant main effect of movement type was found ($F(1, 18) = 4.658, p = .045$). No significant main effects were found for HMD weight ($F(1, 18) = 1.091, p = .310$) or the interaction between the two variables ($F(1, 18) = .515, p = .482$). The minima pertaining to treadmill walking were generally higher than the minima for WIP. However, despite the significant main effect of movement type, the post-hoc analysis ($\alpha = .025$) revealed no significant differences. Similar results were found for maxima. A significant main effect of movement type was found ($F(1, 18) = 8.812, p = .008$), but the main effect of HMD weight was not significant ($F(1, 18) = .893, p = .357$) and no interaction was found ($F(1, 18) = .028, p = .868$). The post-hoc tests ($\alpha = .025$) suggested that treadmill walking was significantly higher than WIP for the means pertaining to the heavy HMD ($p = .019$).).

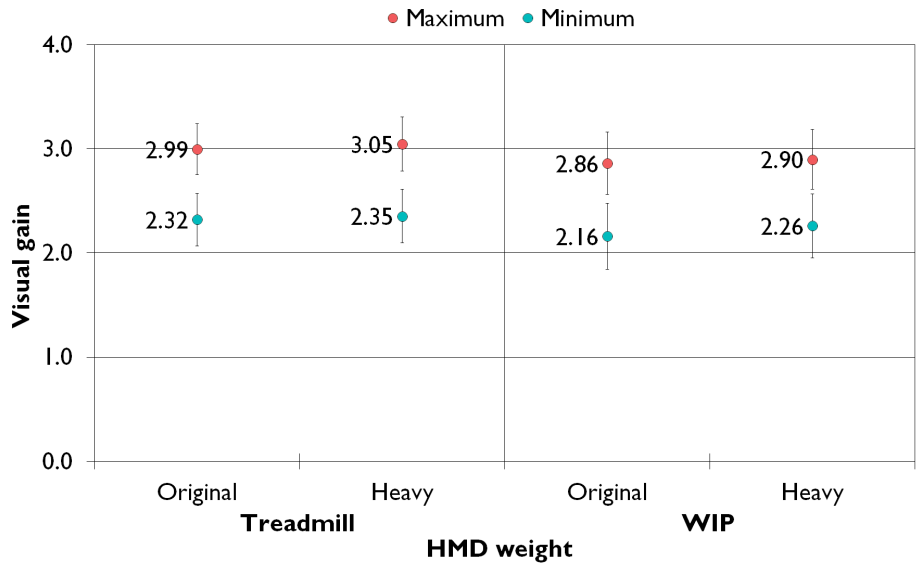


Figure 11. Minimum and maximum visual gains perceived as natural for the two HMD weights across treadmill and WIP. Error bars indicate 95% confidence intervals.

Discussion of S6

The results revealed no difference in the amount of underestimation of virtual speeds across the two HMD weights. However, the study only compared a relatively heavy display with an even heavier version of the same display. Thus, they do not reveal whether there is a difference in case of lighter displays. Even though the post-hoc analyses related to movement type only found a significant difference between the two conditions involving the heavy display, the minima and maxima pertaining to treadmill walking were generally higher than the ones pertaining to WIP locomotion as in S1 to S5.

5. Gain Presentation Method

The purpose of the seventh study was to compare three different approaches to identifying the range of perceptually natural walking speeds during virtual locomotion.

5.1 Study 7 (S7): Gain Presentation Method

While Powell et al. (2011) found no significant differences when comparing two different approaches to presenting visual gains, it cannot be ruled out that the choice of method might be of influence. S7 relied on a within-subjects, 2×3 factorial design crossing two movement types (treadmill and WIP) with three gain presentation modes (GPMs) (different ways of presenting the visual speeds).

Methods and Materials for S7

Twenty participants (16 males, 4 females) aged between 19-43 years (M=28.2 years, SD=7.0) took part in the study. The three GPMs compared in S7 are largely identical to the ones employed in S1 to S6 and bear semblance with existing psychophysical methods (Ehrenstein & Ehrenstein, 1999)):

Randomized Order: The participants were exposed to 15 gains, repeated twice, yielding a total of 30 walks. The gains ranged from 1.0 to 4.0 in increments of 0.2 and were presented in randomized order. The participants verbally reported whether they found the visual speed `too slow', `natural', or `too fast'. This approach resembles the one used in S1.

Reversed Staircases: This GPM is similar to the previous one. However, the gains organized into an ascending and a descending series; i.e., if the series started with 1.0, the gains would gradually increase, and if it started with 4.0, then it would gradually decrease. Ascending series were terminated the first time a `natural' report was followed by `too fast', and descending series were terminated when a `natural' rating was followed by `too slow'. It was randomly decided whether the first series would be ascending and a descending. This approach resembles the one used in S3.

User Adjustment: The third GPM is similar to the method used in S2 and S4 to S6; i.e., the participants were adjusting the gain, which could range from 1.0 to 4.0, while walking. As in the other GPMs the participants performed one walk with ascending gains and one with descending gains.

Results of S7

The minima and maxima were defined as follows: For Randomized Order the minimum and maximum were defined as the mean of the two lowest gains and highest gains, respectively. For Reversed Staircases the minimum was defined as the mean of the two lowest gain rated `natural' (one for ascending and the descending series). The maxima was similarly was based on the two highest gains rated `natural'. For User Adjustment the minimum and maximum were defined as the means of two lower and upper limits, respectively. The corresponding results are summarized in Figure 12. Mauchly's tests indicated that the assumption of sphericity had been violated for GPM in relation to the maxima ($\chi^2(2) = 14.68,\ p < .01$), and degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .64$). No significant interactions between GPM and movement type were found. In relation to the minima, a

significant main effect was found for GPM ($F(2, 38) = 8.807$, $p = .001$), while none was found for movement type. For treadmill walking the post-hoc analyzes ($\alpha = .008$) suggested that the minimum of Randomized Order was significantly lower than the ones corresponding to User Adjustment ($p = .001$) and Reverse Staircases ($p < .001$). For WIP the minimum of Randomized Order was significantly lower than Reversed Staircases ($p < .001$).

In regards to the maxima, significant main effects were found for GPM ($F(1.284, 24.395) = 4.968$, $p < .001$) and movement type ($F(1, 19) = 33.288$, $p < .001$). The post-hoc analyzes ($\alpha = .005$) suggested that the maximum resulting from User Adjustment was significantly lower than the other two maxima in regards to both treadmill walking and WIP (all $p < .001$). The maxima pertaining to Randomized Order differed significantly across the two motion types ($p < .001$).).

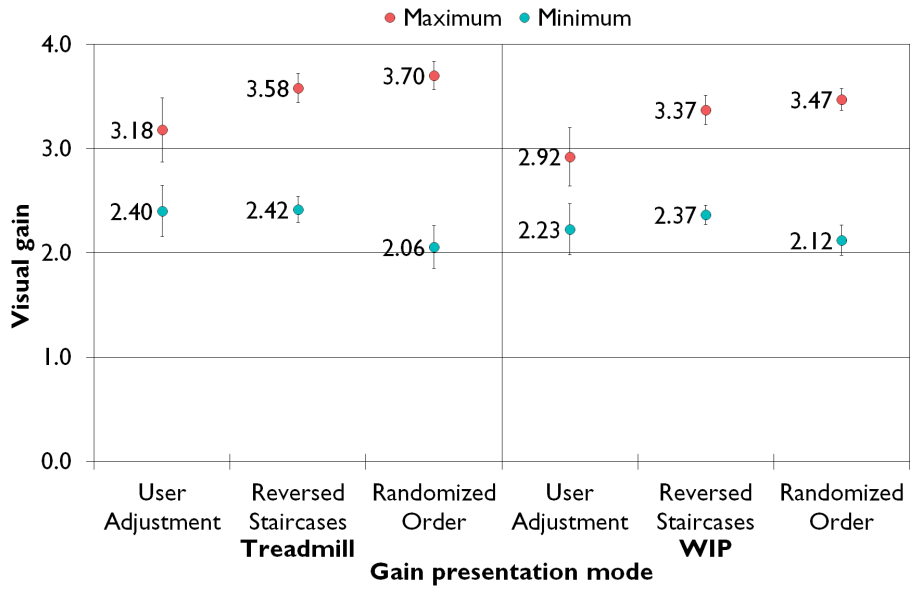


Figure 12. Minimum and maximum visual gains perceived as natural for the three gain presentation modes across treadmill and WIP. Error bars indicate 95% confidence intervals.

Discussion of S7

The results suggest that for both treadmill walking and WIP, Randomized Order caused the participants to find higher and lower gains natural compared to the two other GPMs. Notably the same appear to be the case when comparing the results of S1 and S3, which relied on methods resembling Randomized Order and Reversed Staircase, respectively. Despite this similarity, it is notable that S7 generally led to higher minima and maxima compared to S1 and S3. It seems possible that differences in the range of presented gains are responsible for the varying results. S1 and S3

relied on gains ranging from 1.0 to 3.0 while S7 relied on gains from 1.0 to 4.0. Thus, habituation and increased exposure time may account for the difference. Notably, the results of S7 do not differ considerably from those of S2, S4, S5 and S6 which involved gains from 0.1 to 4.0. Thus, habituation appears to be less of an issue during User Adjustment. A possible explanation is that the participants could skip across the unnatural lower gains more rapidly, and varying exposure times may therefore be the confounding variable. Nevertheless, S7 points to an interesting difference between the three GPMs. User Adjustment yielded smaller ranges of perceptually natural gains and may, therefore, produce more conservative estimates than the other two. The caveat is that the 95% confidence intervals pertaining to User Adjustment are considerably larger than the ones resulting from the other measures. Hence, even though User Adjustment appears more conservative, this may come at the expense of confidence. The limitations of this approach are not unknown within psychophysical research where forced-choice methods are commonly used (Gescheider, 2013). Notably, forced-choice methods have also been used to study perception within IVR (Steinicke, Bruder, Jerald, Frenz, & Lappe, 2010).

The results pertaining to the effects of movement type were not all significant but showed the same pattern as the remaining studies; i.e., with exception of one, all means pertaining to treadmill walking were higher than the corresponding means of WIP.

6. Meta-Analyses

All of the presented studies investigated the extent to which walkers underestimate virtual speeds during treadmill and WIP locomotion. Interestingly, the same tendency was present across all studies, namely, when walking on a treadmill the participants tend to find higher speeds natural compared to when they were walking in place. However, the results are equivocal in regards to the statistical significance of this effect. Four in seven studies found a significant effect of movement type for minima or maxima. Even if a greater majority of the studies had yielded significant main effects, the frequency of significant tests does not provide us with the whole picture. Meta-analyses enable us to combine the findings of several studies through quantitative analysis and thereby achieve greater precision with respect to the observed effect. Traditionally, meta-analysis have been performed as part of large-scale literature reviews, but the value of applying meta-analysis on a smaller scale has been

recognized (Cumming, 2012). Two meta-analyses of the difference between treadmill and WIP locomotion were performed: one for the lower threshold of perceptually natural gains and one for the upper threshold. S1 to S7 do, to the best of our knowledge, represent the only comparisons of gain perception across treadmill walking and WIP locomotion. Thus, no additional studies were included in the meta-analyses.

The results of these meta-analyses are presented as forest plots illustrating the individual effect sizes as confidence intervals (CIs), and the meta-analytic combination, the summary effect size, as another CI (Cumming, 2012). The following subsections describe how the effect size of each study was determined, how composite effect sizes were calculated in order to ensure independence and better weighting of the studies, and finally the results of the meta-analyses are presented.

6.1 Effect size

The effect size of interest was obviously the extent to which the perceived naturalness of visual gains differs across treadmill walking and WIP locomotion. Since we cannot be certain that this difference is identical for the lower and upper thresholds of normal gain perception, the effect sizes for the two are treated separately. Specifically, as a measure of effect size we relied on the mean difference (M_{diff}) between the lower and upper thresholds for treadmill walking (*T*) and Walking-in-Place (*WIP*); i.e., the mean of the differences between the *n* pairs of thresholds for each condition:

$$M_{diff} = \frac{1}{n}\sum_{i=1}^{n} T_i - WIP_i$$

The corresponding CIs were based on the variance (V_{diff}) of these paired differences. Because S1 relied on a single factor design this study yielded one effect size, namely, the M_{diff} between the Treadmill and WIP conditions. The remaining studies were based on factorial designs since they also involved manipulation of a second variable. Thus, the remaining studies yielded as many effect sizes as there were levels in the second variable being manipulated. To exemplify, S3 relied on a 2×4 factorial design crossing the two movement types (Treadmill and WIP) with four different display FOV. Each of the four display FOV enabled a comparison between Treadmill and WIP. Thus, this study yielded four effect sizes. The same logic applies to the remaining factorial designs crossing the two movement types with other factors. An overview of the conditions in the seven studies can be seen in the rightmost column of Table 1.

Group ID	Study no.	Study designs	Conditions
Group I	S1	Single factor design	4 movement types*
Group II	S3	2×4 factorial design	2 movement types × 4 display FOV
Group III	S7	2×3 factorial design	2 movement types × 3 gain presentation methods
Group IV	S2	2×3 factorial design	2 movement types × 3 step frequencies**
	S6	2×2 factorial design	2 movement types × 2 HMD weights
Group V	S4	2×3 factorial design	2 movement types × 3 geometric FOV
	S5	2×3 factorial design	2 movement types × 3 degrees of peripheral occlusion

Table 1. Grouping of effect sizes based on studies and conditions. *This study compared four different movement types, but the meta-analysis only included the difference between treadmill walking and WIP. ** The study relied on a 2×3 factorial design. However, in practice the participants were only exposed to two conditions since the condition with the unaltered HMD from S6 represented one of the three step frequencies.

6.2 Composite effect sizes

Each of the seven studies did, as suggested, yield more than one effect size. However, Borenstein, Hedges, Higgins, and Rothstein (2011) describe that we cannot treat these effect sizes as separate studies in the meta-analyses for two reasons: 1) It would lead us to assign greater weight to studies with more outcomes than studies with fewer outcomes. 2) Considering the effect sizes as the outcome of separate studies would lead us to erroneously treating them as independent, despite several effect sizes resulting from the reports made by the same participants. Since all seven studies were based on within-subject designs, it was necessary to collapse the effect sizes resulting from each study into composite effect sizes. Moreover, in two cases participants took part in two studies entailing that independence could not be assumed. Thus, in those two instances it was necessary to collapse the effect sizes across studies. Table 1 provides an overview of how the effect sizes were collapsed across studies and conditions into five groups. Each group supplied one composite effect size for the meta-analyses. The composite effect sizes ($\bar{Y}$) and variances ($V_{\bar{Y}}$) were determined based on an approach described by Borenstein et al. (2011). That is, the composite effect sizes for the groups were given as the mean effect size of the studies in that group:

$$\bar{Y} = \frac{1}{m}\sum_{j=1}^{m} Y_j$$

where *m* is the number of effct sizes per group. According to Borenstein et al. (2011) the corresponding composite variance ($V_{\bar{Y}}$) of the effects sizes *j = 1, ... m* can be defined as:

$$V_{\bar{Y}} = \left(\frac{1}{m}\right)^2 \left(\sum_{j=1}^{m} V_j + \sum_{j \neq k} (r_{jk} \sqrt{V_j} \sqrt{V_k})\right)$$

The where r_{jk} is the correlation coefficient describing the amount of correlation between the jth and kth variances (V_j and V_k).

6.3 Results of the Meta-Analyses

The meta-analyses were performed by means of the ESCI software which runs under MS Excel (Cumming & Finch, 2011) and relied on the random effcts model, which assumes two sources of variability; i.e., variability caused by sampling error and variability caused by diffrences at a study level (Wilson, 2010). Heterogeneity, the extent to which sampling variability cannot reasonably account for the variability of the studied effect sizes (Cumming, 2012), was evaluated based on I^2. In line with recommendations presented by Burcharth, Pommergaard, and Rosenberg (2014), we regarded I^2 values of 25% 50% and 75% as indicative of `low', `moderate', and `high' heterogeneity (Higgins, Thompson, Deeks, & Altman, 2003), and only considered the results usable if $I^2 < 75\%$. Figure 13 illustrates the data and forest plots making up the meta-analyses of the extent to which the lower and upper bounds of natural gain perception differ between treadmill walking and WIP locomotion.

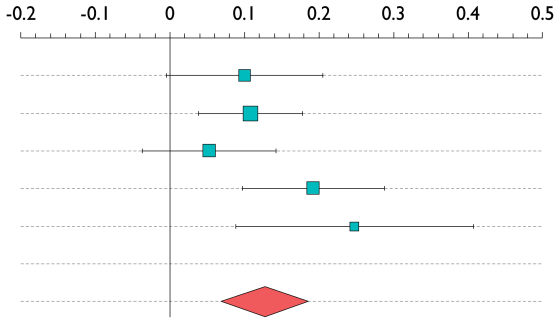
Since the effct size was defined as $T - WIP$ positive differences suggest that the participants found higher speeds to be natural during treadmill walking compared to WIP. In case of both composite effcts (blue squares) and the summary effect sizes (red diamonds) statistical significance at 95% CI is visible from the figure; i.e., if the CI overlaps with the vertical line at zero.

The meta-analysis pertaining to the lower threshold of natural gain perception found that the minima was higher during treadmill walking compared to WIP with a summary effct size of 0.128 (95% CI[0.069, 0.186], $p < 0.001$, $I^2 = 50.4\%$). The meta-analysis of the upper threshold similarly suggested that the maxima was higher for treadmill walking with a summary effct size of 0.159 (95% CI[0.094, 0.224], $p < 0.001$, $I^2 = 63.3\%$).

MINIMA:	$\bar{Y}$	95% CI	Weight (%)	n
Group I	0.100	[-0.005, 0.205]	18.8	22
Group II	0.108	[0.039, 0.118]	27.0	21
Group III	0.053	[-0.037, 0.143]	22.1	20
Group IV	0.192	[0.097, 0.288]	20.9	19
Group V	0.248	[0.099, 0.407]	11.1	20
Summary	**0.128**	**[0.069, 0.186]**		

Test for heterogeneity: X^2 = 8.06, df = 4 (p = .09), I^2 = 50.4%

Test for overall effect: Z = 6.03 (p < .001)



MAXIMA:	$\bar{Y}$	95% CI	Weight (%)	n
Group I	0.009	[-0.129, 0.147]	14.3	22
Group II	0.125	[0.059, 0.191]	25.8	21
Group III	0.232	[0.152, 0.313]	23.2	20
Group IV	0.184	[0.109, 0.259]	24.4	19
Group V	0.216	[0.060, 0.371]	12.5	20
Summary	**0.159**	**[0.094, 0.224]**		

Test for heterogeneity: X^2 = 10.91, df = 4 (p = .03), I^2 = 63.3%

Test for overall effect: Z = 4.79 (p < .001)

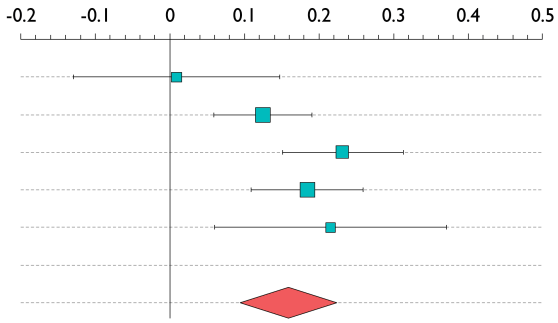


Figure 13. Meta-analyses (data and forest plot) for the minima (top) and maxima (bottom). The composite effect sizes ($\bar{Y}$) of the groups are represented with blue squares and the error bars signify the corresponding 95% CIs. The sizes of the squares are scaled based on the weight assigned to the individual groups of *n* participants. The pooled estimates and 95% CIs are determined via the random-effects model and are visualized by the red diamonds. The figure shows significant overall effects.

When meta-analyses are based on five or less studies it is considered good practice to perform the analyses using both random- and fixed-effects models (Crocetti, 2015). Consequently, the results were corroborated through analyses relying on the fixed effects model. These analyses yielded the same overall results; i.e., the minima and maxima were higher for treadmill walking that WIP. Specifically, the summary effect size for minima was 0.121, 95% CI [0.081, 0.160] and for maxima it was 0.159, 95% CI [0.094, 0.224].

6.4 Discussion of Meta-Analyses

Since the meta-analyses relying on the fixed- and random-effects models suggested the same overall results, we simply base the following discussion on the more conservative estimates produced using the random-effects model.

The meta-analyses suggested that there indeed is a difference in the upper or lower limits of perceptually natural gains of the two movement types. Particularly, the meta-analyses were able to confirm the suspicion about the direction of the effect raised by S1 to S7: the participants perceived higher speeds to be natural when walking on the treadmill compared to when they were walking in place.

Moreover, the meta-analyses provided estimates of magnitudes of the observed diffrence. That is, the CIs of the summary effcts suggested that we with reasonable confidence can assume that the diffrence between the gains that are perceived as natural was between 0.069 and 0.186 for the minimum, and the difference was between 0.094 and 0.224 for the maximum. Here it is worth considering the magnitude of the effct size relative to the identified ranges between the upper and lower bounds of perceptually natural gains of the studies. The mean range between minima and maxima across all studies is 0.67 (SD=0.31) for treadmill walking and 0.65 (SD=0.23) for WIP and the only ranges larger than 1.0 were found in S7 for the conditions Reverse Staircases and Randomized Order. Thus, it would seem that the effct of movement type is relatively large compared the range of gains perceived as natural by the participants. However, compared to the actual thresholds the effect appear rather small. The lowest identified gain across the seven studies (1.51) was found for the unconstrained view of the Oculus DK1 during WIP locomotion in S3, and the highest gain (3.70) was found for treadmill walking in the condition Randomized Order of S7.

From a perceptual standpoint the results of the meta-analyses are of interest since they suggest that the type of gesture being performed may influence how we perceive visual motion in IVR. Assuming that subtraction of non-visual motion information contributes to speed underestimation (Durgin, 2009), this may suggest that WIP leads to a larger degree of subtraction than treadmill walking. Possibly, due to the higher exertion accompanying WIP locomotion (Nilsson, Serafin, Laursen, et al., 2013). From the perspective of developers this result is interesting because it suggests that the perceptually natural gains identified based on treadmill walking need not be directly applicable in relation to WIP locomotion and vice versa.

7. Conclusions

This paper detailed seven studies and two meta-analyses pertaining to the underestimation of virtual walking speeds during treadmill and WIP locomotion.

S1 and S2 investigated how the perceptual distortion of visual speeds is influenced by gait cycle properties; i.e., different movement types and step frequency. S1 found no significant difference between the compared movement types, but S2 found a significant main effect of step frequency. An increase in step frequency appears to result in increased speed underestimations, but a significant difference was only found between the highest step frequency and the two lowest ones in case of both treadmill and WIP locomotion.

S3 to 6 investigated the effects of four different visual display properties: DFOV, GFOV, peripheral occlusion and HMD weight. For both treadmill and WIP locomotion, the results suggest that the size of both the DFOV and GFOV are inversely proportional to the degree of underestimation of the virtual speeds for. No significant main effects of peripheral occlusion and HMD weight were identified.

S7 compared three different ways of presenting visual speeds to the participants. When the participants were allowed to adjust the virtual speeds, they found a lower range of gains to be natural compared to when the speeds were varied between walks either randomly or in ascending and descending series. While user adjusted speeds may provide a more conservative estimate of the range, this appear come at the expense of confidence due to the increased variability in the data introduced by this method.

All seven studies compared treadmill and WIP locomotion. Across the studies a pattern was visible; i.e., the participants seemed to find higher speeds natural during treadmill walking compared to WIP. However, the results were equivocal in regards to the significance of this effect.

Through meta-analyses of the difference between the upper and lower bounds of the perceptual natural speeds for treadmill and WIP locomotion, we were able to demonstrate that there indeed is a difference between the two movement types and present pooled estimates of the magnitude of this difference.

8. References

Andersen, G. J., & Braunstein, M. L. (1985). Induced self-motion in central vision. Journal of Experimental Psychology: Human Perception and Performance, 11(2), 122.

Banton, T., Stefanucci, J., Durgin, F., Fass, A., & Profftt, D. (2005). The perception of walking speed in a virtual environment. Presence: Teleoperators & Virtual Environments, 14 (4), 394-406.

Borenstein, M., Hedges, L. V., Higgins, J. P., & Rothstein, H. R. (2011). Introduction to meta-analysis. John Wiley & Sons.

Brandt, T., Wist, E. R., & Dichgans, J. (1975). Foreground and background in dynamic spatial orientation. Perception & Psychophysics, 17 (5), 497-503.

Bruder, G., & Steinicke, F. (2014). Threefolded motion perception during immersive walkthroughs. In Proceedings of the 20th ACM symposium on virtual reality software and technology (pp. 177-185).

Burcharth, J., Pommergaard, H.-C., & Rosenberg, J. (2014). Performing and evaluating meta-analyses. Surgery.

Crocetti, E. (2015). Systematic Reviews With Meta-Analysis Why, When, and How?. Emerging Adulthood, 4(1), 3-18.

Cumming, G. (2012). Understanding the new statistics: Effect sizes, confidence intervals, and meta-analysis. Routledge.

Cumming, G., & Finch, S. (2011). Esci: Exploratory software for confidence intervals [computer software]. Melbourne, Australia: La Trobe University. Retrieved from http://www.latrobe.edu.au/psy/esci.

Dichgans, J., & Brandt, T. (1978). Visual-vestibular interaction: Effects on self-motion perception and postural control. In Perception (pp. 755-804). Springer Berlin Heidelberg.

Diels, C., & Parkes, A. (2010). Geometric field of view manipulations affect perceived speed in driving simulators. Advances in transportation studies(22), 53-64.

Durgin, F. H. (2009). When walking makes perception better. Current Directions in Psychological Science, 18(1), 43-47.

Durgin, F. H., Reed, C., & Tigue, C. (2007). Step frequency and perceived self-motion. ACM Transactions on Applied Perception (TAP), 4 (1), 5.

Ehrenstein, W. H., & Ehrenstein, A. (1999). Psychophysical methods. In Modern techniques in neuroscience research (pp. 1211-1241). Springer.

Gescheider, G. A. (2013). Psychophysics: the fundamentals. Psychology Press.

Higgins, J. P., Thompson, S. G., Deeks, J. J., & Altman, D. G. (2003). Measuring inconsistency in meta-analyses. BMJ: British Medical Journal , 327 (7414), 557.

Jones, J. A., Swan, I., Edward, J., & Bolas, M. (2013). Peripheral stimulation and its effect on perceived spatial scale in virtual environments. Visualization and Computer Graphics, IEEE Transactions on, 19(4), 701-710.

Kassler, L., Feasel, J., Lewek, M. D., Brooks Jr, F. P., & Whitton, M. C. (2010). Matching actual treadmill walking speed and visually perceived walking speed in a projection virtual environment. In Proceedings of the 7th symposium on applied perception in graphics and visualization (pp. 161-161).

Kingdom, F. A. A., & Prins, N. (2010). Psychophysics: a practical introduction. Academic Press London.

Mourant, R. R., Ahmad, N., Jaeger, B. K., & Lin, Y. (2007). Optic flow and geometric field of view in a driving simulator display. Displays, 28(3), 145-149.

Nilsson, N. C., Serafin, S., Laursen, M. H., Pedersen, K. S., Sikström, E., & Nordahl, R. (2013). Tapping-in-place: Increasing the naturalness of immersive walking-in-place locomotion through novel gestural input. In Proceedings of the 2013 IEEE symposium on 3d user interfaces.

Nilsson, N. C., Serafin, S., & Nordahl, R. (2013). The perceived naturalness of virtual locomotion methods devoid of explicit leg movements. In Proceedings of motion in games. ACM.

Nilsson, N. C., Serafin, S., & Nordahl, R. (2014a). Establishing the range of perceptually natural visual walking speeds for virtual walking-in-place locomotion. Visualization and Computer Graphics, IEEE Transactions on, 20(4), 569-578.

Nilsson, N. C., Serafin, S., & Nordahl, R. (2014b). The influence of step frequency on the range of perceptually natural visual walking speeds during walking-in-place and treadmill locomotion. In Proceedings of the 20th ACM symposium on virtual reality software and technology (pp. 187-190).

Nilsson, N. C., Serafin, S., & Nordahl, R. (2015a). The effect of head mounted display weight and locomotion method on the perceived naturalness of virtual walking speeds. In 2015 IEEE virtual reality short papers and posters.

Nilsson, N. C., Serafin, S., & Nordahl, R. (2015b). The effect of visual display properties and gain presentation mode on the perceived naturalness of virtual walking speeds. In 2015 IEEE virtual reality short papers and posters.

Öberg, T., Karsznia, A., & Öberg, K. (1993). Basic gait parameters: reference data for normal subjects, 10-79 years of age. Journal of rehabilitation research and development , 30, 210-210.

Powell, W., Stevens, S., B. abd Hand, & Simmonds, M. (2011). Blurring the boundaries: The perception of visual gain in treadmill-mediated virtual environments. In Proceedings of the 3rd IEEE VR workshop on perceptual illusions in virtual environments (pp. 4-8).

Pretto, P., Ogier, M., Bülthoff, H., & Bresciani, J. (2009). Influence of the size of the field of view on motion perception. Computers & Graphics, 33(2), 139-146.

Proffitt, D. R., Stefanucci, J., Banton, T., & Epstein, W. (2003). The role of effort in perceiving distance. Psychological Science, 14 (2), 106-112.

Riecke, B. (2010). Compelling self-motion through virtual environments without actual self-motion: using self-motion illusions (``vection'') to improve user experience in vr. Virtual reality, 149-176.

Steinicke, F., Bruder, G., Jerald, J., Frenz, H., & Lappe, M. (2010). Estimation of detection thresholds for redirected walking techniques. IEEE Transactions on Visualization and Computer Graphics, 16 (1), 17-27.

Steinicke, F., Bruder, G., Kuhl, S., Willemsen, P., Lappe, M., & Hinrichs, K. (2011). Natural perspective projections for head-mounted displays.

Visualization and Computer Graphics, IEEE Transactions on, 17 (7), 888-899. Waller, D., & Hodgson, E. (2013). Sensory contributions to spatial knowledge of real and virtual environments. In Human walking in virtual environments (pp.3-26). Springer.

Wendt, J., Whitton, M., & Brooks, F. (2010). Gud wip: Gait-understanding-driven walking-in-place. In Proceedings of the 2010 IEEE virtual reality conference (pp. 51-58).

Willemsen, P., Colton, M. B., Creem-Regehr, S. H., & Thompson, W. B. (2004). The effects of head-mounted display mechanics on distance judgments in virtual environments. In Proceedings of the 1st symposium on applied perception in graphics and visualization (pp. 35-38).

Wilson, D. (2010). Meta-analysis. In A. R. Piquero & D. Weisburd (Eds.), Handbook of quantitative criminology (p. 181-208). Springer New York.