Blurring the Boundaries: The Perception of Visual Gain in Treadmill-Mediated Virtual Environments

Wendy Powell — University of Portsmouth, UK

Brett Stevens — University of Portsmouth, UK

Steve Hand — University of Portsmouth, UK

Maureen Simmonds — McGill University, Canada

ABSTRACT

There is a perceptual distortion of the speed of optic flow in VR which may have implications for the ecological validity of treadmill-mediated virtual environments. This study investigated the extent of the perceptual distortion, and the upper and lower boundaries of perceived normal gain when the rate of optic flow is manipulated. There was a range of gain which was perceived as normal (1.55 - 2.41), and even the minimum perceived normal gain was significantly higher than the true normal gain of 1:1 ($t(19) = 7.51$, $p<0.001$). This should be taken into consideration when designing treadmill-mediated virtual environments.

KEYWORDS: Optic flow, gain perception, treadmill, VR

INDEX TERMS: I.3.7 [Three-Dimensional Graphics and Realism]: Virtual Reality, I.3.6 [Methodology and Techniques]: Interaction techniques, General Terms: Human Factors

1 BACKGROUND

Previous studies have observed that there is an altered perception of the speed of optic flow when treadmill walking in a virtual environment [e.g. 1, 2]. For optimal design of treadmill-mediated interaction, if the perceived realism of the rate of progression through the environment is important, it is necessary to fully understand both the magnitude and direction of this altered perception.

According to the Motor Prediction Theory [3], the perceptual consequences of motor actions can be anticipated, and this prediction can be used to filter or cancel the sensory consequences of movement. For example, when walking at a known speed, the anticipated optic flow would be 'subtracted' from the actual optic flow, so that in a normal walking environment the surroundings would appear stationary.

Durgin, Gigone and Scott [2] undertook a series of experiments to investigate this theory, and their results predominantly supported this subtractive model. Interestingly though, they found that treadmill walking produced a lower level of visual subtraction than overground walking at similar speeds. If, as they propose, visual subtraction is related to self-speed, then this finding might suggest that walking on a treadmill gives a slower self-speed estimation. However, this is in direct contrast to the findings of Alton, Baldey, Caplan & Morrissey [4], who observed that treadmill speeds were felt to be higher than the same overground speed.

wendy.powell@port.ac.uk, brett.stevens@port.ac.uk, steve.hand@port.ac.uk

Durgin, Gigone and Scott [2] suggested that the lack of physical forward motion may be contributing to the lower levels of visual subtraction during treadmill walking, and this does seem to be supported by their finding that the visual subtraction during overground walking is approximately equal to the sum of the visual subtractions for treadmill walking and for passive forward movement. If this is the case, then there are perhaps different mechanisms used for self-speed estimation and for visual speed prediction, with motor prediction contributing to visual subtraction but not accounting entirely for the phenomenon.

The findings of a follow-up study do suggest other mechanisms that may contribute to the perception of visual speed. Durgin, Fox, Schaffer and Whitaker [5] investigated the effect of adding clutter to a virtual environment on the matching of visual and kinesthetic estimates of the speed of self-motion ("gain matching"). Their results suggested that a more cluttered environment significantly improves gain matching in overground walking, but not during treadmill walking. They suggest that the cluttered environment may not simply be providing an increase in the visual cues for improved depth perception, but rather that they may represent obstacles to be avoided. They postulated that in the overground condition an 'obstacle avoidance mechanism' would be activated, which may improve the accuracy of speed estimation. Since the participants walking on the treadmill were holding static handrails throughout the trials, haptic feedback may have reduced the need to use a visual-based avoidance system.

Whilst this theory may have some merit, the experimental design makes it difficult to directly compare the two conditions. The overground tests accelerated from standing for each trial, whilst the treadmill trials involved continuous motion. In addition, the walking speed overground was variable and controlled by the participant, and could be as low as 1.1m/s. However, speed on the treadmill was fixed at 1.34m/s (around 30% higher). It has previously been observed that the walking speed of the participant can affect the accuracy of gain matching [6], and this may have been a factor in the difference between the two walking conditions.

In an attempt to address some of these issues, Durgin, Reed and Tigue [7] undertook a further series of studies investigating the phenomenon of gain matching during treadmill walking. They note that the previous work on visual subtraction discrepancies when treadmill walking only account for around 15% error, but gain matching errors are generally found to be considerably higher than this [e.g. 2, 5, 6].

The ratio of step length / step frequency (walk ratio) is remarkably constant for an individual [8], but treadmill walking is associated with a higher step frequency relative to stride length, and hence a lower walk ratio [e.g. 4, 9]. Durgin et al. postulated that self-speed estimates may be based on step frequency, and thus the 10% decrease in walk ratio seen in treadmill walking would be perceived as a 10% increase in speed [7]. Indeed, their study did find that visual gain could be accounted for by combining the walk ratio decrease with the 15% error in visual subtraction.

The visual gain seen in Durgin et al.'s study is in fact somewhat lower that those observed in the earlier studies, and the authors attribute this to the closer link between perception and action in their improved treadmill apparatus. However, although they allowed each trial to accelerate from stationary to prevent a visual standard being established, the treadmill speed was still not under the control of the participant, and thus the results are still not reliably comparable to normal overground walking.

In addition, each trial consisted of a 1 second ramp-up from stationary and then 4 seconds walking at the target speed, so 20% of each trial was actually during the acceleration phase, which may have affected speed judgments. In this series of studies using a higher fidelity treadmill apparatus [7], it was again found that the more cluttered virtual environment was associated with more accurate gain matching in both overground and treadmill walking, but it is not really clear whether this was due to more accurate speed perception, or because the addition of objects closer together in near space artificially increase the absolute rate of optic flow. A further study comparing static speed estimation of empty and cluttered environments would be necessary to establish this.

Whilst there is some disagreement as to the absolute value of gain mismatch when treadmill walking in VR, it is clear that all these studies identify gain errors in the same direction, i.e. visual speeds are perceived as slower than they actually are. This does indicate that for treadmill-mediated VR to appear normal to a user, a multiplier > 1 should be used when setting the visual gain between the treadmill and the environment.

Whilst previous studies have been able to identify a perceived "most normal" visual flow gain, for usability it may be more useful to identify what is the perceived "tolerance of normal". In each of the studies above, the participants were given the option of identifying 'fast' or 'slow' in response to the changing optic flow speeds. This method is suitable for determining a perceptual boundary, but it is less able to identify a range of acceptable tolerance.

A recent study focused on a rating of "matched" rather than fast or slow [10], using a treadmill-mounted dial to allow users to adjust the optic flow multiplier until the gain was perceived to be normally matched. Whilst this study used a different approach to quantify the optimum normal gain setting, it still aimed to define a single value for this perceived matched gain.

However, it has previously been observed that people are not sensitive to gain changes of less than 15% [11]. Indeed, in one study a 50% change of simulated self-motion was required for a change to be perceived [12], although this study used expanding flow fields rather than immersive VR, and this may account for the lowered ability to detect changes.

Furthermore, it is not known whether different gains may be rated as normal even when they are perceptually different from each other.

If there is a range of tolerance in the perception of normal visual gain, then treadmill-mediated VR which is designed to operate within this range of gain may be less likely to cause visuo-motor dissonance. However, although the deviation from the mean in previous studies may indicate a level of difficulty in identifying a single normal gain, this is most likely to represent the limits of *perception* of gain change, which is not necessarily equivalent to the limits of *tolerance* of gain change.

For example, in one study the gains were started at 0.61, 1.63 and 1.0, and then stepped up or down depending on the visual judgment of the participant (lower gain if the participant felt it was too fast, and higher gain if they felt it was too slow) [7]. It is quite conceivable that the gain of 1.63 may have been perceived in the higher end of perceptually normal, but given the forced choice option between responding 'slow' or 'fast', the response of 'fast' is the more reasonable one.

Likewise, the gain of 0.61 may have fallen into the lower range of perceptually normal, but in this case the forced choice response 'slow' would be required. It is not possible to establish the true range of normal gain tolerance without an experimental design that allows for both an upper and lower boundary of normal to be established.

2 METHOD

The objective of this study was to investigate whether normal gain perception during treadmill walking has a range of tolerance.

2.1 Study design

In Durgin's studies, gains ranging from 0.61 to 1.63 were used as starting points [7]. However, the distributions in Kassler's study suggest that gains may be rated as normal across a much wider range than this [10]. This experiment therefore used gains between 0.2 and 3.0.

It is possible that alerting participants to each gain change may not elicit the same results as waiting for them to notice a gradual change. Therefore the gains were presented in two different modes, automatic and prompted. In the 'prompted' mode, the gain was only changed after the participants gave a verbal judgment of the current visual speed. In the 'automatic' mode, the gain was gradually changed regardless of any feedback from the participant.

Durgin et al.[5] found that visual clutter in an environment improved the accuracy of gain perception, but they did not know if this was due to an increase in the visual cues or the addition of obstacles to be avoided. Therefore in this study two different virtual environments were used (Figure 1). One had a monochrome walkway with virtual pillars spaced 5m apart, and no other visual distractions. The other scene had bright textures and detail applied to walls, floor and ceiling, with frequent visual cues consistently throughout the environment. In this way, there was a large difference in the quantity and frequency of visual cues, but no difference in the presence of virtual obstacles or the dimensions of the walkway.

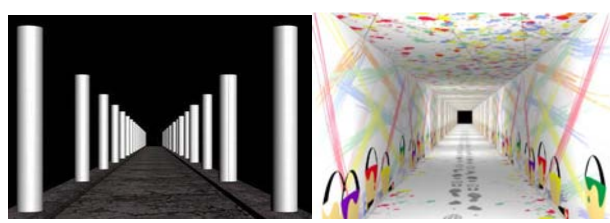

Figure 1: Monochrome pillars and coloured corridor scene

A multi-factorial within-subjects design was used (Table 1). Environment type, gain presentation method and gain were the independent variables, and perceived normal gain was the dependent variable.

	Automatic gain change	Prompted gain change
Low detail scene	condition 1 (Gain 0.2-3.0)	condition 2 (Gain 0.2-3.0)
High detail scene	condition 3 (Gain 0.2-3.0)	condition 4 (Gain 0.2-3.0)

Table 1: The combination of scene type and gain change method used in the experimental conditions.

2.2 Materials and Apparatus

Previous studies have used fixed treadmill speeds, but this places a constraint on the walking speed of the participants. Since evidence suggests that there is no significant difference in gain matching between different walking speeds [7, 10], unconstrained walk speeds should elicit similar results. Therefore, to allow more natural walking, the treadmill used in this experiment was adapted from a motorised treadmill. The manual controls were removed and replaced with a separate control system connected to a potentiometer. This detected the rate of change of position of the participant on the treadmill belt and thus was able to set the treadmill speed dynamically to the self-selected pace of the participant.

The treadmill was placed 2m in front of a 4.5m by 2m display screen (giving an effective field of view of around 100^{o}). Both scenes were created as 3-dimensional models using 3D Studio Max and rendered into an interactive format using Open Scene Graph. The virtual camera was set at the starting position of the participant, with a fov of 100^{o} and a height of 1.6m. The interactive stereoscopic scene was back projected onto the screen using a pair of Christie 7700 Lumen projectors with polarising filters. To minimise visual distraction, the room was darkened for the experiment, with the main light source being the display screen itself.

The speed of the treadmill belt was monitored using an optical sensor and used as input to update the virtual camera view in real-time. This speed was updated every frame (30fps) at a resolution of 0.01 m/s.

2.3 Participants

Twenty healthy volunteers from the University of Portsmouth staff and students (11 male 9 female) between the ages of 19 and 55 (mean age 33.2) participated in this study.

2.4 Procedure

Prior to the task all participants spent a few minutes familiarising themselves with the equipment and walking on the treadmill. Experimental trials were not initiated until the participant was able to maintain a steady comfortable walking pace on the adapted treadmill. They were then familiarised with the experimental task using a demonstration program which presented very fast, normal and very slow gains.

The virtual scenes were linked to the treadmill via a software 'gearing' system, which enabled precise control of the visual gain in the scene relative to the rate of treadmill walking. In each condition the participants were presented with 30 gain changes, ranging from 0.2 (10m in real world moves 2m in the virtual world) to 3.0 (10m in real world moves 30m in the virtual world). Each trial started at a gain of 0.2 and increased by 0.2 at each gain change. Once a gain of 3 was reached, the gain was decreased by 0.2 at each gain change until the gain returned to 0.2.

In the 'prompted' mode, the participants gave a verbal judgement of the on-screen speed after each gain change:

1. "Slow" (on-screen movement appears too slow)
2. "Normal" (on-screen movement appears to match walking speed)
3. "Fast" (on-screen movement appears too fast)

The gain changes were initiated by the recording of the previous response, so the participants were in control of how long they need to make a perceptual judgement. Each trial took approximately 3-5 minutes to complete.

In the 'automatic' mode, participants were instructed to report their verbal judgement of the on-screen starting speed, and then to report any time they noticed that the relative speed had changed (for example, from slow to normal, or from fast to slow etc). The gain changed 0.2 every 4 seconds.

Participants walked in each of the experimental conditions in counterbalanced order. For each condition the participants started to walk on the treadmill in front of a static image of the test scene. When the participant reported that they were walking comfortably, the treadmill movement was interactively linked to the scene via the gearing software. Throughout the trials the participants wore lightweight cardboard polarised glasses to enable stereoscopic viewing.

3 Results

For each trial, a weighted mean value was calculated for the gain values that were reported as appearing 'normal'. The minimum and maximum gain perceived as normal were also identified (Table 2).

	Cond. 1	Cond. 2	Cond. 3	Cond. 4
Mean	1.98	1.99	1.83	1.92
Min	1.59	1.57	1.41	1.52
Max	2.40	2.45	2.31	2.34

Table 2: Mean, Min and Max Values of gain perceived as normal during each condition.

A repeated-measures 2-way ANOVA (environment x presentation method) demonstrated no significant effect for environment type ($F(3, 17) = 0.85$ $p = 0.49$) or for presentation method ($F(3\ 17) = 1.11$ $p=0.37$) .

Since there was no difference between the presentation conditions, or the virtual environments, the data was collapsed for the subsequent analysis and testing (Table 3).

	Data from all conditions collapsed for analysis
Mean	1.96 (0.26)
Min	1.55 (0.31)
Max	2.41 (0.33)

Table 3: Mean, Min and Max Values of gain perceived as normal during each condition (StDev in brackets).

The mean normal gain was compared to the real 'normal' gain using a one-sample t-test. The overall mean gain for the test population was 1.96:1. This was significantly different from the actual normal gain of 1:1, ($t(19) = 16.25$ $p<0.001$).

The minimum and maximum gains were compared using a paired-sample t-test. There was a significant difference between the minimum (1.55) and maximum (2.41) perceived normal gain ($t(19)=10.29$ $p<0.001$).

The mean of the minimum gain perceived as normal was 1.55:1. This was significantly different from the actual normal gain of 1:1 ($t(19) = 7.51$, $p<0.001$).

4 Discussion

This experiment supported previous findings that 1:1 geared ('normal') optic flow is perceived as too slow when walking on a self-paced treadmill, and also confirmed that there a range of visual gain which can be perceived as normal. Furthermore, upper and lower boundaries of the perceptual tolerance of normal gain were identified, both of which were above the normal 1:1 ratio.

There are a number of factors affecting the perception of visual gain in treadmill mediated VR. Firstly, treadmill walking itself gives the perception of around a 10% increase in walk speed compared to actual speed [1]. This means that walking at 1m/s gives the feeling of walking at 1.1m/s. Indeed, it has previously been noted that people tend to walk slower on a treadmill than overground [13], which may be a consequence of this psychomotor misperception.

Secondly, there is a distance compression phenomenon in VR which means that for each metre walked in VR, the participant's visual perception would be that 0.74 meters had been travelled [2, 14], effectively reducing the perceived optic flow speed.

Thus it is not surprising that the mean gain perceived as normal is significantly higher than 1. However, what is less clear is the real value of this normal gain, which has been reported to be as low as 1.3 [5] and as high as 2 [10].

In this experiment it was found that the mean perceived normal gain was 1.93:1. This was significantly different from the real normal gain of 1:1, and was also higher than the perceived gain found in many previous studies [e,g 5,6]. Kassler et al.'s study found a similar gain to that found in this experiment [10], although their virtual environment was a more open scene, which would produce lower lamellar flow which is known to decrease accuracy of perception of visual gain [6].

There were a number of differences between this experimental design and those that have been carried out previously, and it may well be that this has contributed to the difference seen in the results. Previous studies have used preset speeds for the treadmill walking, with no control being given to the participant to select a preferred speed [2, 5, 6, 7, 10, 15]. Even with the visual gain linked directly to the treadmill speed, this would result in unnaturally constant walk speed and optic flow. Whilst this fixed ratio may allow a more consistent comparison to be made between trials, it is forcing a more artificial style of walking.

Furthermore, most of the previous studies used fixed handrails for support, and this additional haptic feedback may have contributed to the discrepancy in perceived gain. In contrast, the treadmill used in this experiment had sliding handrails which allowed normal and free movement of the upper extremity during walking.

The main difference, however, is that the previous studies generally used variations on a design which identified a single perceptual boundary [2, 5, 6, 7, 10]. This experiment found that there is in fact a range of gain that can be perceived as normal. Whilst the standard deviations in the results of previous studies are likely to identify the range within which gain differences cannot be perceived, they do not identify the range of normal gain 'tolerance'.

In this study it was found that, whilst participants were often aware of a change of gain, they classified the changes as within the tolerance of normal gain. The range of normal perceived gain was between 1.52 and 2.41, i.e. a change of +/- 20%. This is higher than the 15% sensitivity to gain changes found previously [11], as the participants in this experiment were not asked to identify the point of noticeable change, but rather the point of departure from 'normal' gain. The fact that the gain values are higher supports the suggestion that there is a tolerance for a range of gain which is perceived as normal, beyond the range of 'no perceptible difference'.

The range of perceived normal gain found in this study was consistent regardless of whether the response was prompted every change or whether participants themselves noticed that the gain was no longer slow/normal/fast. In addition, there was no significant difference between the different environments.

This finding of a significant range of normal visual gain has implications for the design of treadmill-mediated Virtual Reality. Even the minimum value of gain identified as perceived normal is still well above the normal gain of 1.0, and this does support the suggestion that software gearing between treadmill and virtual environment should be considered where perceptual realism is important.

It is clear from previous studies that there is considerable variation between individuals in the perception of visual gain [e.g. 10], and this may make it difficult to identify a single optic flow multiplier which is optimum for all users. However, the results of this study suggest that it may not be necessary to identify a precise gain value between the software and hardware to produce a realistic and believable visual flow for each individual. If the system is designed for a gain value at roughly the mean of the range of perceived normal, it is likely to fall within the tolerance range of most users.

5 Conclusion

This is the first study to identify the range of visual gain values which lie within the tolerance of normal gain perception. Gain perception may be influenced by a variety of software, hardware and human factors, nevertheless these findings suggest that the tolerance of users to gain change may reduce the risk of visuo-motor dissonance in treadmill-mediated VR.

References

[1] H.K. Distler A. Pelah , A. Bell and A. Thurrell. The perception of absolute speed during self-motion (abstract). in *European conference on visual perception*. 1998. Oxford, UK.

[2] F.H. Durgin., K. Gigone, and R. Scott, Perception of visual speed while moving. *J Exp Psychol Hum Percept Perform*,. 31(2): p. 339-53, 2005

[3] D.M. Wolpert and J.R. Flanagan, Motor Prediction. *Current Biology*, 11: p. R729-R732, 2001

[4] F. Alton, L. Baldey, S. Caplan and M. Morrissey, A kinematic comparison of overground and treadmill walking. *Clinical Biomechanics*, 13(6): p. 434-440, 1998

[5] F.H. Durgin,L. Fox, E. Schaffer and R.Whitaker. The perception of linear self-motion. in *Proceedings of SPIE*. San Jose, California, 2005

[6] T. Banton, J. Stefanucci, F. Durgin, A. Fass and D. Proffitt, The Perception of Walking Speed in a Virtual Environment. *Presence: Teleoperators & Virtual Environments*, 14(4): p. 394-406, 2005

[7] F. Durgin, C. Reed, and C. Tigue, Step frequency and perceived self-motion. *ACM Trans. Appl. Percept*., 4(1): p. 5, 2007

[8] N. Sekiya, and H. Nagasaki, Reproducibility of the walking patterns of normal young adults: test-retest reliability of the walk ratio(step-length/step-rate). *Gait & Posture*, 7(3): p. 225-227, 1998

[9] H.Stolze, J. Kuhtz-Buschbeck, C. Mondwurf, A. Boczek-Funcke, K. Johnk, G. Deuschl and M. Illert., Gait analysis during treadmill and overground locomotion in children and adults. *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control*, 105(6): p. 490-497, 1997

[10] L. Kassler, J. Feasel, M. Lewek, P. Frederick J. Brooks, J., and M. Whitton,, "Matching actual treadmill walking speed and visually perceived walking speed in a projection virtual environment," presented at the *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization*, Los Angeles, California, 2010.

[11] M. Kearns, F. Durgin, and W. Warren, Sensitivity to the gain of optic flow during walking. *Journal of Vision*, 2(7): p. 431-431,. 2002

[12] J. Monen and E. Brenner, Detecting changes in one's own velocity from the optic flow. *Perception*,. 23(6): p. 681-90, 1994

[13] W.Powell, B. Stevens and M. Simmonds, Treadmill interface for virtual reality vs. overground walking: A comparison of gait in individuals with and without pain, *Studies in Health Technology and Informatics*, 144: p 198-203, 2009

[14] H. Frenz, M. Lappe, M Kolesnik and T. Buhrmann., Estimation of travel distance from visual motion in virtual environments. *ACM Trans. Appl. Percept*., 4(1): p. 3, 2007.

[15] A. Thurrell and A. Pelah. Matching visual and nonvisual signals: evidence for a mechanism to discount optic flow during locomotion. in *Human Vision and Electronic Imaging* X.. San Jose, Ca: SPIE, 2005