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Simulating self motion I: cues for the perception of motion

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Abstract

When people move there are many visual and non-visual cues that can inform them about their movement. Simulating self motion in a virtual-reality environment thus needs to take these non-visual cues into account in addition to the normal high-quality visual display. Here we examine the contribution of visual and non-visual cues to our perception of self-motion. The perceived distance of self motion can be estimated from the visual flow field, physical forces or the act of moving. On its own, passive visual motion is a very effective cue to self motion, and evokes a perception of self motion that is related to the actual motion in a way that varies with acceleration. Passive physical motion turns out to be a particularly potent self motion cue: not only does it evoke an exaggerated sensation of motion, but it also tends to dominate other cues.

1. Introduction

A fundamental goal of virtual reality is to provide a user with a compelling sensation of an alternate environment. The process of simulating the changing visual view that an observer would see if they were really moving around the simulated environment has tended to dominate virtual reality research, while other cues associated with self-motion are often ignored, although some haptic-self motion cue systems have been constructed (e.g., [1,2]) and auditory-self motion cues have been studied as well (see [3]). It is, however, a tribute to the flexibility of the human sensory system that providing only visual information works as well as it does. Indeed, even just moving the user's view from one point to another without the user actually selecting where to go, or physically moving at all, can provide a compelling sense of self motion.

There are two basic aspects to simulating motion in a virtual reality system. Firstly, how do viewers inform the virtual reality generator where they are and where they would like to move to in the environment? And secondly, how are viewers' movements within the environment actually simulated so as to provide them with a convincing and accurate sensation that they really have moved?

These problems are inter-related since how viewers control the simulation contributes to their experience. If the user just sits in a chair and controls their motion around the virtual world with a joystick then almost all the cues to motion need to be simulated. At the other end of the spectrum, if viewers inform the generator about their movements by actually making complete and natural movements then many of the natural non-visual cues to motion will be present and there will be no need to simulate them. Even in this case differences between actual and simulated environments need to be taken into account. For example, making people walk over real sand when simulating a desert scene might not be a practical solution.

In practice, the design of most virtual reality systems falls somewhere between these extremes, allowing the viewer to make some natural movements while simulating others. Typically for example, virtual reality explorers are allowed and encouraged to move their heads but not to leave a small working area.

In this paper we review the various sensory cues normally associated with self motion. We then describe a series of experiments that quantify how much each cue contributes to the perception of self motion and assess how important it is to include each cue in a successful virtual reality simulation.

2. The cues to self motion

2.1 Vision

There are two classes of visual cues to self motion: displacement and optic flow. Displacement refers to the fact that during movement the location of visual features are displaced relative to the viewer. When judging self motion, particular features can be chosen as landmarks and the motion can be estimated in response to 'sightings' of these landmarks. However, navigation by sighting these features is clumsy since it requires regular checks and feedback. Using visual displacement does not allow easy anticipation of the results of a movement.

A second visual cue to motion results from the continuous movement of the images of all objects in the environment relative to the viewer which creates a complex pattern of retinal motion referred to as optic flow [4, 5]. Optic flow contains information about the amplitude and direction of the linear and rotational components of the self motion that created the flow [6, 7]. People can use optic flow, even when it is the only cue, to assess their direction of travel [8 - 11], although whether optic flow is used to guide navigation in humans is uncertain [6, 12 - 15]. The magnitude of the translational component of self motion is

present in the flow field but the mathematics of extracting it, especially in the presence of rotational components or object motion, is not trivial [16].

When optic flow occurs in the absence of other sensory cues to motion, it can evoke postural adjustments [17, 18] and the perception of actual self-motion even though the viewer is stationary. This visually induced illusory sensation of motion is called *vection* and has associated perceptions of displacement and speed [19, 20]. It has recently been shown that honeybees can use optic flow to judge flown distances [21 - 23]. We describe below experiments that show that humans can also judge distance travelled from optic flow cues [24].

2.2 Gravito-inertial force

Any movement of the body that changes its velocity induces forces on the body itself and on the organs and structures within it. This includes gravity but not constant velocity movement which cannot generate any such forces. Within the body there are a number of sensory systems that can transduce the physical forces acting upon it. Some systems are specialized for doing so, such as the vestibular system and, less well known, a system based in the kidneys. Other systems are incidentally stimulated, for example the skin where it receives pressure from a support surface [25, 26].

The vestibular system is a set of specialized gravito-inertial detecting organs located in the vestibule of the inner ear (see [27 - 29] for comprehensive reviews). The system is made up of the semicircular canals and the otoliths which detect angular and linear accelerations of the head respectively [30]. Both parts are mechanical force transducers and are thus only sensitive to accelerations. Neither part is sensitive to the other type of acceleration: the otoliths are not sensitive to angular accelerations and the semicircular canals are not sensitive to linear accelerations.

Accelerations on the body are also sensed internally by specialized visceral graviceptors especially in the region of the kidney [31]. It is unlikely that these organs provide a very quantitative directional estimate of linear accelerations and, of course, they are subject to the same confusion between gravity and self motion as other accelerometers. Their properties have been investigated by centrifuging patients with spinal lesions at various levels with their otoliths close to the axis of rotation and thus not subject to centrifugal forces [31].

The somatosensory (touch) system includes a number of mechanoreceptors that detect pressure and stretch on the skin and in muscles, joints and visceral organs when the body is accelerated [25]. Seated subjects undergoing accelerations have the cutaneous receptors in the back, bottom and feet stimulated by the forces generated by the acceleration. Although there is evidence from patients with spinal lesions that the somatosensory system does not contribute significantly to our perception of self motion [32], the lack of such sensation when undergoing accelerations may detract from the veracity of the simulation.

Detecting air flow over the skin is a special case of somatosensory perception. Although at normal walking velocities the flow of air over the skin is probably too slow to provide useful cues to motion, at faster speeds, especially those taking place without a windshield (such as when simulating cycling, skiing or the flight of a hang glider), there is a strong expectancy of air flow over the skin which may also provide quantitative perceptual cues about the motion. Airflow is important to birds who will start flying when airspeed reaches a certain magnitude [33, 34] and can enhance their visual reflexes to movement [35].

Since all the above gravito-inertial force-sensitive systems are normally activated together, it is really of only academic interest which sub-system makes which contribution to the overall perception [36]. People can use physical motion alone to assess a position change [37 - 43] or their direction of travel [44, 45].

The gravito-inertial-somatosensory system as a whole, comprising all the components described above, has three drawbacks when applied to the task of detecting and measuring self motion in an environment.

- It detects forces and therefore only acceleration from which position has to be derived.
- It cannot distinguish gravity from any other accelerations and thus always provides a 'vector sum' of gravity with any other applied forces.
- The vestibular system reports only about the movement of the head and thus motion about the body itself must be derived from the partially known relationship between the head and body.

The fact that the otoliths only sense accelerations can theoretically be turned to advantage when simulating motions in virtual reality and in more traditional flight simulators. As long as the appropriate onset cue accelerations are presented to the operator, periods of constant velocity can be ignored. The position of limited-range equipment can be reset during such movements using accelerations below threshold (around 0.1 m/s^2 [46] although reported values range from 0.014 to 0.25 m/s^2 [29]). This procedure is known as 'washout'.

The fact that gravity is indistinguishable from other accelerations can also potentially be turned to advantage by tilting the observer and encouraging them to believe that the component of acceleration of gravity now in the horizontal plane of the head is actually due to a linear movement [47].

2.3 Proprioception

Proprioception refers to knowledge of the body in general. As such many of the systems considered above qualify as proprioceptors – even some aspects of visual processing. Here we refer specifically to that part of the proprioceptive system comprising the mechanoreceptors of the joints and muscles from which

the position of the individual joints and therefore limbs can be reconstructed [48]. Proprioception can provide powerful information about self motion [49]. For example, knowing the movement of the feet during walking and the length of the stride carries enough information to calculate the distance covered.

There is a very variable linkage between limb movement and distance travelled however, in this way proprioceptive information concerning movement can only be interpreted in context. The relationship is very different between running and walking for example, and almost non-existent when using a vehicle. Even when riding a bicycle, gears change the relationship between limb and body movements. Clearly, if proprioception is to be useful, a very flexible calibration between limb movement and distance is needed. We describe below some experiments showing that after training, limb movement can be used with some degree of precision.

2.4 Efferent Copy

In 1950, Holst and Mittelstaedt ([50] and see [31] for an updated review), demonstrated that actively moving insects have access to a simultaneous copy of their motor commands. This pioneering work led to an extensive search for evidence of an efference copy in all animals. Cells have recently been found in the parietal cortex of monkeys that change their sensory fields before an intended gaze shift [51]. Also cells receiving vestibular information seem to be able to distinguish between self generated and externally applied movements [52, 53] implying the existence of an efferent copy modifying the sensory information during the movement.

Having access to a copy of the efferent command allows the brain to prepare for the consequences of an intended motion before it has occurred. A mismatch between expected (efferent) and actual (sensory) movement is probably one of the major causes of motion sickness [54] and probably also contributes to cybersickness [55].

Like proprioception, an efferent copy has a very variable linkage with the resulting movement and needs to be interpreted in context. The copy of the motor command to move the hands when turning the steering wheel of a car has to be matched with the sensory information that is far removed from the musculature of the arms to inform the brain that the car has gone round a corner successfully according to plan.

Efference copy is a central but often neglected component in the design of virtual reality systems. The control system that has been chosen, for example driving a vehicle, pedalling a bike or pushing a joystick, needs a motor output from the observer and a copy of this output will then be matched with the sensory result. The expected sensory result of a self motion is a multisensory barrage that includes components from all the systems mentioned above. Calibrating the connection between the motor signal out and the sensory signal that comes back often requires extensive learning by the subject.

3. How much does each of the cues contribute to self motion perception?

Here we summarize a set of experiments we have conducted to assess the contribution of optic flow activating the visual system, gravito-inertial cues activating the gravito-inertial-somatosensory system, limb movements activating the proprioceptive system and the knowledge of the intention to move. In these experiments we measure our perception of self motion by measuring how far a subject perceives themselves to have moved in response to controlled presentation of the various cues. Critical to these experiments has been the development of a device to present visual and non-visual cues within a virtual reality environment over extended physical distances. This was accomplished through the design and use of a virtual reality system based on a tricycle "Trike", the details of which are described in a companion paper[56].

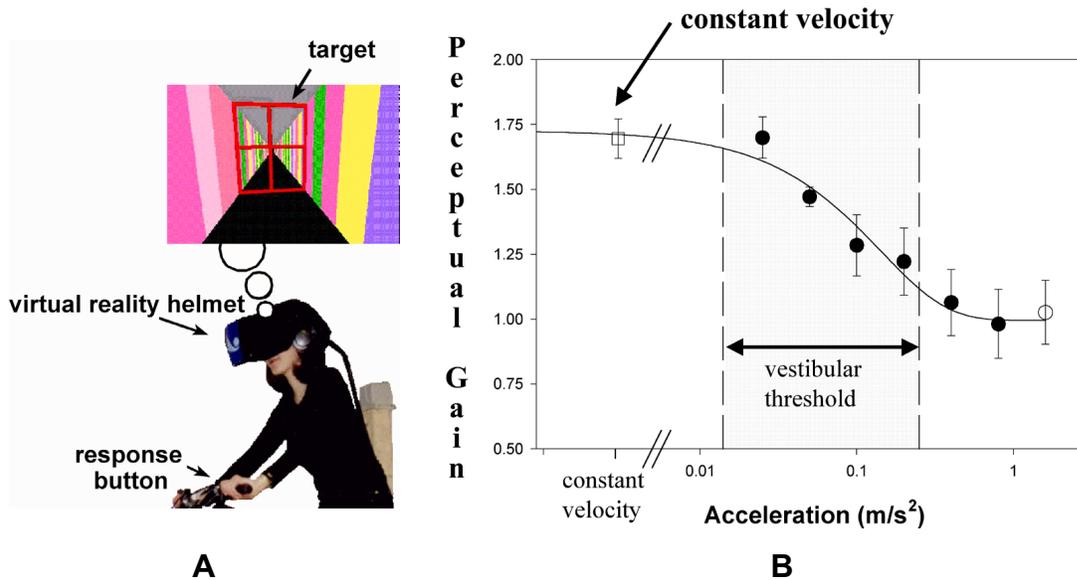


Figure 1. **A** shows the experimental set up. Subjects sat passively on a bicycle (cf. Fig 5). Target distances were presented in a virtual environment as a frame in a corridor. When the subject had a good estimate of the distance, obtained using perspective and parallax cues, the target disappeared and visual movement down the corridor commenced. Subjects indicated when they had gone through the target distance. **B** The data are expressed as the ratio between the perceived movement (the target distance) to the actual motion (the optic flow) which we refer to as the perceptual gain plotted as a function of the simulated acceleration down the corridor. Redrawn from [21].

Measuring how far someone perceives themselves to have moved presents some interesting methodological considerations. Asking people to estimate how far they have moved requires them to make a relative judgement against an internalized yardstick. Distortions in the representation of the yardstick, such as stimulus compression or expansion [38, 57] when judging multiples of the yardstick, complicate the interpretation of such data. Such a technique cannot be used to predict the accuracy with which people perceive their movement through a particular given target distance. Asking subjects to reproduce previously

travelled distances [40] also does not address the veridicality of perception since an inaccuracy or systematic bias in the perception of the initial distance may be matched by similar inaccuracies and bias in the measurement trials.

For all the experiments described below, the following technique was used. Subjects were presented a given target distance that they were asked to remember. Visual targets were presented within the virtual reality display as a large frame within a corridor. This is illustrated in Figs. 1a and 2 and in the inserts to Fig 3. Subjects were encouraged to obtain parallax cues as to the distance of this target as well as using the perspective cues. The target was then removed and various cues to self motion were presented in each experiment. Subjects indicated when they had travelled through the previously indicated distance.

3.1 Measuring the effectiveness of visual cues to motion

In order to measure how well subjects judge distance travelled with only visual cues, we first presented them with the visual target in a virtual corridor to generate an internal representation of a distance (Fig 1 [24]). The target was then removed and the subjects were then presented optic flow commensurate with travelling down the corridor. They were then asked to indicate when they had moved through the remembered target distance. In addition to presenting optic flow consistent with constant velocity movement down the corridor, we also used a smooth, linear movement with a constant acceleration in order to generate data that could be compared to gravito-inertial-somatosensory data (see below) where accelerations are required for the system to work at all.

Interestingly, how far subjects thought they had moved depended on the movement profile. We describe the response as a 'perceptual gain' (vertical axis of Fig 1b) in which the distance they perceived themselves to have moved (i.e., the target distance they were originally given) is expressed as a fraction of the distance they actually moved (the cumulative effect of optic flow they considered equivalent to this distance). A high perceptual gain thus corresponds to subjects

perceiving they have gone further than the actual motion, and a low perceptual gain corresponds to less sensation of motion.

There are two main features depicted in the data shown in Fig 1. Firstly, lower accelerations ($< 0.1 \text{ m/s}^2$) and constant velocity (0.4-6.4m/s) motion profiles are associated with higher perceptual gains than higher accelerations ($> 0.1 \text{ m/s}^2$). This is illustrated by the shape of the curve in Figure 1 which forms a sigmoid between the higher and lower gains as a function of acceleration. Secondly, lower accelerations ($< 0.1 \text{ m/s}^2$) are associated with perceptual gains greater than unity whereas higher accelerations are associated with accurate judgements, that is, a perceptual gain of close to unity. The former effect indicates a variation of the effectiveness of visual optic flow cues as a function of acceleration of self motion, the latter indicates a miscalibration between actual and perceived motion.

The variation in perceptual gain with acceleration cannot be explained as a general distortion of space within the virtual reality display. The target distances were the same for all motion profiles and yet led to very different perceptual judgements. The effects must be due to the optic flow itself. All the constant velocity trials were associated with similar perceptual gains which were statistically independent of velocity over the range tested (0.4-6.4m/s). While it remains possible that motion noise, such as jerkiness introduced by pixelation, might affect perceived motion [58 - 60], the consistency across all speeds shown in our constant velocity data suggests that our results for low acceleration movement are unlikely to be explained by such inadequacies of the display. The results are consistent with a variation in the processing of optic flow that depends on the self motion profile. Constant acceleration conditions were chosen to cover the range from the lowest accelerations that were practical with the experimental setup, to accelerations above the reported threshold for the vestibular system. Constant velocity conditions were chosen over the range practical with the

experimental setup, and included velocities associated with normal walking and cycling.

Subjects were deprived not only of non-optic-flow visual cues to their motion, but also of vestibular, somatosensory and proprioceptive cues that would normally provide complementary information. For example, the otolith division of the vestibular system, the inner-ear organs stimulated by physical linear acceleration, normally plays a major role in humans' perception of self-motion, providing the movement has accelerations above vestibular threshold [40, 61, 62]. For whole-body linear acceleration, the vestibular threshold seems to be around 0.1 m/s^2 (although studies have reported values ranging from 0.014 to 0.25 m/s^2 [27, 46]). This acceleration range corresponds to the range of optic flow accelerations associated with the transition between high and low perceptual gains (Fig. 1b).

Higher perceptual gains are associated with optic flow accelerations that would normally not be accompanied by other cues, especially vestibular cues. The higher gains suggest that more emphasis is placed on visual information when other information is scarce and that the visual contribution is toned down or given lower weighting when other information is also available (as it is for other aspects of perception, e.g., [63]). The only problem with this apparently logical argument is that optic flow seems to be too effective at evoking a sensation of self motion. Visual perceptual gains are often too large, with constant velocity motion being associated with a perception of moving 1.7 times faster than the stimulus motion. Reducing the perceptual gain to unity hardly represents giving vision a lower weighting that allows other senses to contribute. Why might this be?

Our visual display was quite impoverished. The spatial resolution was quite poor with pixels subtending about 0.3 degs and the field was of limited extent. There were no binocular or stereoscopic cues to the structure of the world and

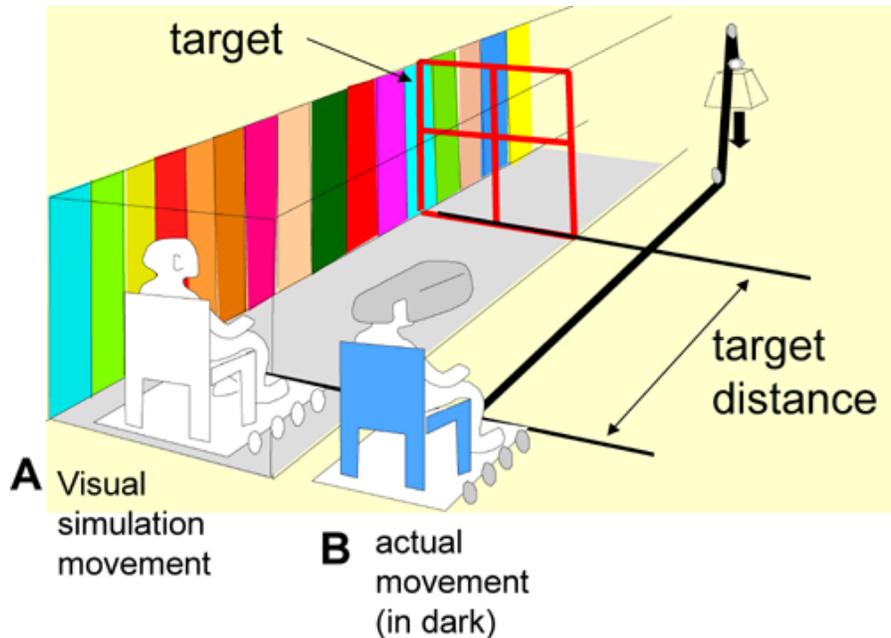


Figure 2. The experimental setup used to investigate the perception of physical motion. Targets were presented in a virtual corridor. When the subject had obtained an estimate of its distance they started the trial. The screen went dark and subjects were pulled along by means of a falling weight attached to their chair by a rope and pulley. Accelerations of between 0.1 and 0.5 m/s^2 for about 3m could be obtained. Visual targets were presented either in a real corridor (see insert to Fig 3) or via an HMD (above).

accommodation was fixed optically. However it seems counter-intuitive that a paucity of visual cues might be enhancing our subjects' sensation of self motion.

The structure of our display was a simple 2m -wide corridor with no texture on the floor or ceiling. These dimensions mean that subjects were less than 1m (orthogonally) from each of the walls. It is well known anecdotally that riding in a low-slung vehicle or travelling along a narrow tunnel can enhance the sensation of speed of motion. The high perceptual gains experienced by our subjects might be related to this observation.

3.2 Measuring the effectiveness of gravito-inertial-somatosensory cues

In order to measure the role of gravito-inertial-somatosensory cues used alone, subjects sat on a chair mounted on a wheeled platform that could be moved at a constant acceleration (Fig 2). They were first given a target distance (either the same one as used in the vision experiments or a real target presented in a real corridor or by being physically moved in the dark through the target distance). They were then moved in complete darkness and indicated when they perceived they had traversed the target distance.

For constantly accelerating movement of between 0.1 and 0.3 m/s² and for visual targets presented either via a HMD or as a real target, the perceptual gain was about 3 (Fig 3). That is, when the chair had moved one metre, it was perceived as moving three times further. Over this same range of accelerations, the perceptual gain of the response to optic flow was between 1.0 and 1.2 (see Fig 1). That is, the perceived distance of physical motion in the dark was perceptually equivalent to three to four times the visual motion. For physically presented targets, subjects were quite successful in reporting the correct distance even when a deliberate mismatch was introduced between the motion profile used for target presentation and test runs (see Fig 3).

Israël et al. [39] matched a visually presented target distance with physical motion over very short distances and also found that subjects needed less physical motion (0.24m) to match a visual distance (0.8m). This overestimation, by a factor of between 3 and 5 for acceleration values around 0.5 m/s², was also found when subjects were asked to estimate displacement in metres [64], for motion in the z-axis [65] and under active motion conditions [41].

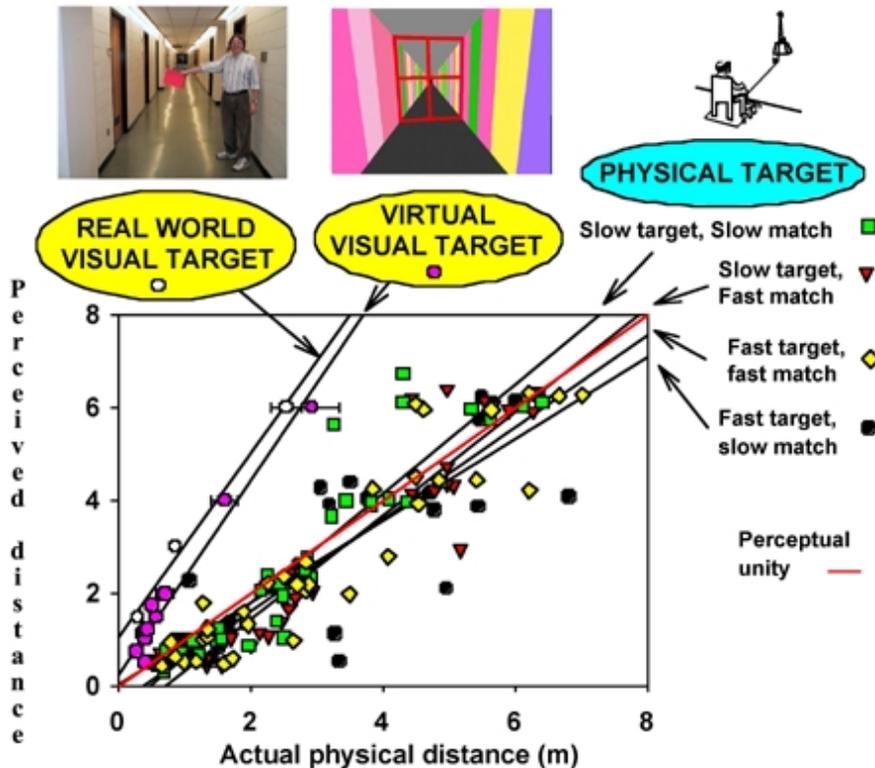


Figure 3. The perceptual response to physical motion. When presented with a target distance by being physically moved through it (physical target), subjects were able to reproduce the target distance accurately (light square, triangle, diamond and filled square symbols, reflecting various combinations of accelerations of the target and test motions). When target distances were presented visually either in the real world (hollow circles: real target) or in the head mounted display (filled circles: virtual target) subjects consistently and dramatically overestimated their movement and indicated that they had passed through the target distance after only travelling about 1/3 of that amount (redrawn from [40]).

3.3 Interactions between visual and vestibular contributions

By moving people on the chair mounted on a wheeled platform while they were wearing a virtual reality helmet (Fig 2) we were able to control visual and non-visual sensory inputs independently. The perceived distance of self-motion when visual and physical cues indicated different distances at the same time, were more closely perceptually equivalent to the physical motion experienced rather than the visual stimulation. Thus when a range of visual movements was paired

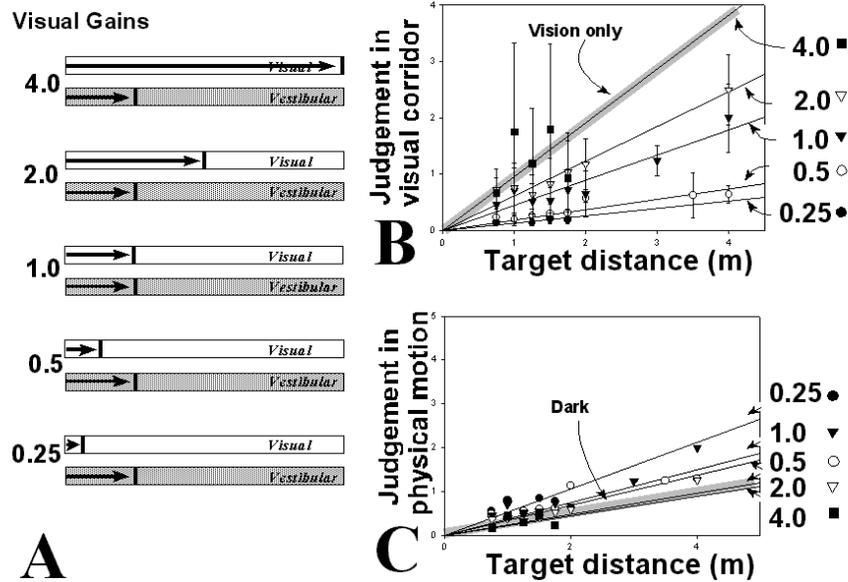


Figure 4. Physical motion and visual cues were presented at the same time but with different distances of motion (A). Thus there were two ‘right ‘ answers when indicating the distance traversed, derived either from the optic flow or the physical cues to motion. Graph B shows the perceived distance (horizontal axis) as a function of the actual visual distance traversed (vertical axis). The same data are replotted in graph C as a function of the physical distance. Data cluster when plotted against the physical distance indicating that physical cues were more important than visual motion in determining the perception of motion (redrawn from [62]).

with a single physical motion, subjects estimated them to be almost the same. There was a small contribution from the visual information that could be modelled as [66, 67]:

$$\text{Perceived distance} = (k_{\text{vis}} * \text{visual } d) + (k_{\text{vest}} * \text{physical } d)$$

Where:

k_{vis} = weighting of visual signal = 0.14

k_{vest} = weighting of vestibular signal = 0.83

visual d = distance signalled by optic flow

physical d = distance subject physically moved

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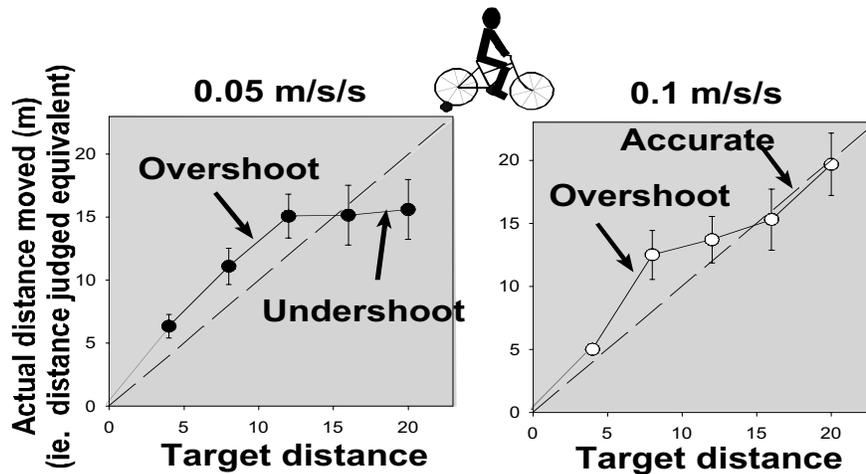


Figure 5. Proprioceptive and efferent copy cues to motion. The distance cycled on a stationary exercise bike in the dark (vertical axis) judged as corresponding to a perceived distance (horizontal axis). For target distances below 15m subjects tended to pedal slightly too far indicating a perceptual gain of less than 1. However the predominant feature is accurate performance with perceptual gain reaching a minimum of 0.8. Two cycling accelerations are shown, 0.05 m/s^2 (left) and 0.1 m/s^2 (right).

3.4 Measuring the effectiveness of proprioceptive cues

In order to assess the significance of the proprioceptive input to the perception of moved distance we repeated our experiments wearing a HMD on a stationary exercise bicycle mounted on rollers. Since the bicycle did not move we had replaced the normal gravito-inertial cues to motion with cues that the bike was not moving. We presented the targets as before and asked subjects to cycle to their remembered locations in the dark. Because of the arbitrary coupling between the pedals and the road wheels we first trained our subjects to pedal at

constant velocity and thus calibrated the pedalling action to an expected movement down a corridor.

The experiments described above looking at visual and physical sensory cues did not show range effects. That is, the perceptual gain appeared to be constant over the full range of distances tested. The effect of pedalling however did depend on the distance of the targets to which the subject was pedalling. For closer targets, subjects tended to overshoot (Fig 5) and pedal past the target. This behaviour corresponds to a perceptual gain of less than one. However for targets around 15 m performance became accurate (perceptual gain 1) and for further targets, subjects actually stopped short of the target, indicating a perceptual gain greater than 1. This was especially true for lower accelerations (0.05 m/s^2). For these low accelerations the visual perceptual gain would be high (Fig 1) and the vestibular contribution close to threshold.

3.5 Intention to move (efferent copy)

The pedalling experiments cannot isolate the role of efferent copy – the neural equivalent of expectation – from the other cues. The proprioception from pedalling is always matched to the efferent copy of the motion commands since the pedalling was performed actively by the subjects. In order to explore these more sophisticated aspects of the cues to self motion we have developed TRIKE. TRIKE is an instrumented tricycle that can be ridden in the real world, while the subject is immersed in a virtual world. By dissociating the direction that the subject moves in the virtual world from his or her movements in the real world, we hope to look at the contribution of efferent copy. This is the subject of ongoing research.

4. Discussion

Using an experimental technique of matching the perceived distance of motion to various cues and their combinations, we have assessed the significance of

each cue to the perception self motion. Optic flow cues evoked an accurate sensation for high accelerations but created the perception of moving too far at low accelerations, especially constant velocity. Since virtual reality often tries to simulate motion of the operator entirely by visual cues, this perceptual overestimation is highly significant especially under conditions when it is important to judge movements accurately. Examples include aircraft taxiing simulation, driving simulators, and using virtual reality to control remote vehicles or robots. In contrast, this overestimation may be highly desirable to create a more exciting ride in entertainment applications.

Surprisingly, physical motion is also overestimated, and by an even greater amount, with perceptual gains around 3 or 4 for accelerations above 0.1 m/s^2 . Thus adding physical motion cues would not be expected to reduce the overestimation of visually induced movement. Indeed, when both visual and physical forces were passively presented simultaneously, the non-visual cues dominated, suggesting various strategies for virtual reality designers to control the perceived distance of motion in virtual reality through manipulation of the physical motion of the operator.

The cues associated with active movement do seem to act as a brake on the high perceptual gains associated with the passive reception of visual and physical forces. When subjects actively pedalled to targets, especially close targets, they were relatively accurate and if anything overshot the targets implying an underestimate of how far they had pedalled. So by using active movements in a virtual environment, the high perceptual gains associated with passive movement might be avoided.

This may be related to the anecdotal phenomenon of distances seeming longer the first time they are travelled in a car. For the outward journey no efferent copy or expectancy can exist and the traveller needs to rely on predominantly visual optic flow cues. These have been found to lead to overestimation of distances

especially at the near-constant velocity of a car. Coming back, after an expectancy has been set up, the distance is no longer overestimated.

Are the accurate perceptions of active movements due to proprioceptive cues from the limbs or using a copy of the motor commands? The TRIKE has been developed partly to answer these questions by allowing us to decouple the link between limb movement and intended movement.

If it is important to use active movements, what movements contribute, perceptually, as 'active'? Clearly natural movements like walking and running are active, but what of the minor motor movements of the feet and hands used for the active control of vehicles such as cars? Consider the act of pushing forwards a joystick to control forward motion. How does this contribute to the perception of self motion? Experiments are underway to compare passive and actively controlled movements using both full physical movement by pedalling the TRIKE or by more subtle manipulations of the expected and actual movement.

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