Multimodal Integration during Self-Motion in Virtual Reality

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Abstract

When moving through our environment, the human brain must integrate information from our muscles and joints (proprioception), the acceleration detectors in our inner ear (vestibular cues) and dynamic visual information (optic flow). While past research has focused on understanding how each of these modalities can be used to perceive different aspects of self-motion independently, very little is understood about how these cues are integrated and the relative influences of each when they are combined. In recent years Virtual Reality (VR) technology and sophisticated self-motion simulators have begun to provide researchers with the opportunity to provide natural, yet tightly controlled stimulus conditions, while also maintaining the capacity to create unique experimental scenarios that could not occur in the real world. The impact of these technologies has been particularly evident in the context of multisensory self-motion perception and spatial navigation. This chapter begins with a brief description of the various simulation tools and techniques that are being used to study self-motion perception. Subsequently, human behavioral work investigating multisensory self-motion perception using these technologies will be summarized, focusing mainly on visual, proprioceptive and vestibular influences during full-body self-motion through space. Finally, the implications of this research for several applied areas will be briefly introduced.

1. Introduction

Our most common, everyday activities and those that are most essential to our survival, typically involve moving within and throughout our environment. Whether navigating to acquire resources, avoiding dangerous situations, or tracking one's position in space relative to important landmarks, accurate self-motion perception is critically important. Self-motion perception is typically experienced when an observer is physically moving through space including, self-propelled movements such as walking, running, or swimming, and also when being passively moved while on train or when actively driving a car or flying a plane. Self-motion perception is important for estimating movement parameters such as speed, distance, and heading direction. It is also important for the control of posture, the modulation of gait, and for predicting time to contact when approaching or avoiding obstacles. It is an essential component of path integration, which involves the accumulation of self-motion information when tracking one's position in space relative to other locations or objects. It is also important for the formation of spatial memories when learning complex routes and environmental layouts.

During almost all natural forms of self-motion there are several sensory systems that provide redundant information about the extent, speed and direction of egocentric movement. The most important of which include, dynamic visual information (i.e. optic flow), vestibular information (i.e. provided through the inner ear organs including the otoliths and semicircular canals), proprioceptive information provided by the muscles and joints, and the efference copy signals representing the commands of these movements. Also important, although less well-studied, are auditory signals related to self-motion and somatosensory cues provided through wind, vibrations and changes in pressure. Currently, much work has been done to understand how several of these individual modalities can be used to perceive different aspects of self-motion independently. However, researchers have only recently begun to evaluate how they are combined to form a coherent percept of self-motion and the relative influences of each cue when more than one is available.

Not only is it important to take a multisensory approach to self-motion perception in order to understand the basic science underlying cue combination, but it is also important to strive towards evaluating human behaviors as they occur under natural, cue-rich, ecologically valid conditions. The inherent difficulty in achieving this is that the level of control that is necessary to conduct careful scientific evaluations is often very difficult to achieve under natural, realistic conditions. Consequently, in order to maintain strict control over experimental conditions, much of the past work has been conducted within impoverished, laboratory environments using unnatural tasks. More recently, however, Virtual Reality (VR) technology and sophisticated self-motion interfaces are now providing researchers with the opportunity to provide natural, yet tightly controlled stimulus conditions, while also maintaining the capacity to create unique experimental scenarios that could not occur in the real world (Bülthoff and van Veen 2001; Loomis et al. 1999; Tarr and Warren 2002). VR also does this in a way that maintains an important perception-action loop that is inherent to nearly all aspects of human-environmental interactions.

Visually simulated Virtual Environments (VEs) have been the most commonly used form of VR, because, until very recently it has been difficult to simulate full-body motion through these environments without having to resort to unnatural control devices such as joysticks and keyboards. More recently, the development of high-precision motion tracking systems and sophisticated self-motion simulators (e.g. treadmills and motion platforms) are allowing far more control and flexibility in the presentation of body-based self-motion cues (i.e. proprioceptive and vestibular information). Consequently, researchers are now able to study multisensory self-motion perception in novel and exciting ways. The significant technological advancements and increased accessibility of many VR systems have stimulated a renewed excitement in recognizing its significant potential now and in the future.

Much of the multisensory research up until this point has focused upon tasks involving discrete stimulus presentations in near body space, including visual-auditory, visual-proprioceptive, and visual-haptic interactions. Far less is understood about how different sources of sensory information are combined during large-scale self-motion through action space. Unlike other approaches used to examine the integration of two specific cues at a particular, discrete instance in time, navigating through the environment requires the dynamic integration of several cues across space and over time. Understanding the principles underlying multimodal integration in this context of unfolding cue dynamics provides insight into an important category of multisensory processing.

This chapter begins by a brief description of some of the different types of simulation tools and techniques that are being used to study self-motion perception, along with some of the advantages and disadvantages of the different interfaces. Subsequently, some of the current empirical work investigating multisensory self-motion perception using these technologies will be summarized, focusing mainly on visual, proprioceptive and vestibular influences during full-body self-motion through space. Finally, the implications of this research for several applied areas will be briefly described.

2. Simulation Tools and Techniques

2.1 Visual Displays

The exciting potential of VR comes from the fact that you can create worlds with particular characteristics that can be systematically manipulated and customized. This includes elaborate worlds unlike anything that can or does exist within the known real world. Rich, realistic visual details can be included, or the visual scene can be intentionally limited to particular visual cues of interest such as the optic flow provided through a cloud of dots, or the relative positioning of selected landmarks. Instant teleportation from one position in space to another (Meilinger et al. 2007), the inclusion of wormholes to create non-Euclidean spaces (Schnapp and Warren 2007), and navigation throughout 4-D environments (D'Zmura, et al. 2000) are all possible. This type of control and flexibility is not something that can be achieved in a real-world testing environment. Whereas, in the past, the process of using computer graphics to create more complex VEs, such as realistic buildings or cities, was time consuming and arduous, new software advancements are now allowing entire virtual cities of varying levels of detail to be built in just a few days (e.g. Müller et al. 2006).

In order to allow an observer to visualize these VEs, different types of displays have been used (for a more thorough review see Campos et al. 2007a). Traditionally, desktop displays have been the most commonly used visualization tool for presenting VEs. These displays typically consist of a stationary computer monitor paired with an external control device that is used to interact with the VE (i.e. a joystick or mouse). Even though the quality and resolution of desktop displays has been steadily increasing in recent years (e.g. high dynamic range displays; see Akyüz et al. 2007), they are non-immersive, have a limited field of view (FOV) and can accommodate very little natural movement.

Other displays such as the Cave Automatic Virtual Environments (CAVE™, Cruz-Neira et al. 1993) and other large curved projection screen systems (e.g. Meilinger et al. 2008 - http://www.cyberneum.com/PanoLab_en.html; See Figure 1) provide observers with a much wider FOV by projecting images on the walls surrounding the observer, and in some cases the floor. Such displays are often projected with two-slightly different images (accounting for the inter-pupillary distance), which, when paired with stereo glasses (anaglyph stereo or polarized stereo) can provide a 3-dimensional display of the environment. Despite the full FOV and high level of immersion provided by these displays, they again, only allow for a limited range of active movements.

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Apart from desktop displays, head-mounted displays (HMDs) are perhaps the most widely used visualization system for navigational tasks. HMDs range in size, resolution, and FOV. Their typically small FOV is one of the main. This restriction can be partially ameliorated by pairing the HMD with a motion tracking system which can be used to update the visual image directly as a function of the observer’s own head movements. This allows for a greater visual sampling of the environmental space and a more natural method of visually exploring one’s environment. HMDs also provide a highly immersive experience because the visual information is completely restricted to that experienced through the display by blocking out all surrounding visual input. The greatest advantage of HMDs is the extent of mobility that is possible, allowing for natural, large-scale movements through space such as walking.

In terms of understanding the role of particular sources of sensory information in self-motion perception, there is often a trade-off between having high resolution, wide FOV displays, which provide the most compelling visual information, and the flexibility of having a visualization system that can move with the observer (i.e. HMD), thus providing natural body-based cues. Therefore, using a combination of approaches is often advisable.

2.2 Treadmills and Self-Motion Simulators

The most natural way in which humans interact with and navigate within their environment is by actually moving. Therefore, understanding self-motion perception can only truly be accomplished by studying an active observer as they physically move through space; something for which a simple visualization device alone will not suffice. From the perspective of multisensory approaches to studying self-motion, it is also important that particular body-based cues can be isolated from each other, for instance, by independently manipulating proprioceptive and vestibular inputs. Several sophisticated self-motion interfaces and motion capture systems are now providing such opportunities.

Of course, the most natural form of movement through a VE is in fact, not simulated movement at all, but actual walking. Several labs have now developed large, fully-tracked, free walking spaces (e.g. the MPI tracking lab - Campos et al. 2009 - http://www.cyberneum.com/TrackingLab_en.html, see Figure 2; the VENlab - Tarr and Warren, 2002; and the HIVE - Waller et al., 2007). Using motion capture information, an observer can walk, rotate and orient in any direction while their movements are used directly to update the information in the visual display (i.e. HMD). This provides a highly natural locomotor experience and retains proprioceptive and vestibular inputs in their purest form. The main limitation of these setups is that the size of the VE is constrained by the size of the actual environment. While this is sufficient for studying behaviors that take place in smaller scale spaces, it would not suffice for understanding the role of self-motion perception during the exploration of larger outdoor spaces or complex buildings, for instance. Some strategies have been used to maximize movement capacities, such as placing a gain on the visuals during rotations. What this does is redirect the walker by causing them to turn a greater or lesser angle physically as a way of containing their movements within the confines of the space (Engel et al.

2008; Peck et al. 2008; Razzaque et al. 2001, 2002). However, the perceptual consequences of such redirected walking manipulations are currently not known.

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The advantage of tracking an observer's position in space as a way of updating their position in the VE is that this also provides a moment-by-moment recording of the behaviors that are being performed during any given task. This is particularly informative when studying self-motion perception because it provides a measure of different movement parameters such as walking speed and the walked trajectory. With full or partial body tracking, additional movement characteristics such as step length, facing direction, pointing direction, and body posture can also be recorded. This provides a rich source of information as it effectively captures even subtle movement characteristics at every instance in time (e.g., Campos et al. 2009; Siegle et al. 2009).

Other devices that are used to allow physical walking through VEs are treadmill setups. Unlike free-walking spaces, treadmills permit unconstrained walking over infinite distances. Standard treadmills typically provide a capacity for straight, forward walking while limiting the walker to one position in space. Essentially this limits the body-based cues to proprioceptive information. Most often these setups also use a handrail for stability and support, which provides additional haptic information informing the observer of their lack of movement through space. When walking in place under such conditions, not only are the kinematics of walking different from walking over ground (e.g. propulsive forces etc.), but the vestibular information that is typically generated during the acceleration phase of walking is missing. In order to account for this, other, much larger treadmills (ranging from 1.5-2.5 meters wide and 3-6 meters long) have been developed, which allow for forward, accelerated walking across the treadmill belt until a constant walking velocity is reached (Hollerbach et al. 2000; Souman et al. 2010; Thompson, et al. 2005). A harness can be used for safety to ensure that the walker does not leave the surface of the treadmill, while still allowing the flexibility of relatively unconstrained movements. Further, systems like the Sarcos Treadport system developed by Hollerbach and colleagues is equipped with a tether that can be used to push and pull the walker in a way that simulates the accelerating or decelerating forces that accompany walking through space (Christensen et al. 2000). This tether can also be used to simulate uphill or downhill locomotion (Tristano et al. 2000).

By pairing these types of setups with a motion tracking system, the treadmill speed can be adjusted online in response to the observer’s own movements. Specifically, control algorithms have been developed as a way of allowing an observer to walk naturally (including stopping and changing walking speeds), while at the same time the treadmill speed is adjusted in a way that causes the walker to remain as centrally on the treadmill as possible (e.g. Souman et al. 2010). These algorithms are also optimized so that the re-centering movements produce accelerations that are not strong enough to create large perturbations during walking causing a loss of balance. In general, as a method of naturally moving through VEs, large linear treadmills can effectively provide proprioceptive information during walking, as well as some important vestibular cues. However, they do not allow for turning or rotational movement trajectories and can create some “noisy” vestibular stimulation during re-centering when using a control algorithm.

Circular treadmills constitute another type of movement device that allows for limitless curvilinear walking through space without reaching any end limits. During curvilinear walking, the vestibular system is always stimulated, thus providing a rich sensory experience through both proprioceptive and inertial senses. Most circular treadmills are quite small in diameter and thus mainly permit walking or rotating in place (e.g. Jürgens et al. 1999). Larger circular treadmill allow for natural, full-stride walking in circles (See Figure 3 for an image of the MPI circular treadmill that is 3.6m in diameter). The MPI circular treadmill is a modified version of that originally developed by Mittelstaedt and colleagues (Mittelstaedt and Mittelstaedt 1996), which includes new control and safety features and a motorized handlebar that can move independently of the treadmill belt/disc. Consequently, this provides a unique opportunity to decouple vestibular and proprioceptive information by having participants walk in place at one rate as they are moved through space at a different rate. This is achieved by having the participants’ rate of movement through space (i.e. inertial input) dictated by the speed at which the handlebar is moved, while the rate at which they walk in place (i.e. proprioceptive input) is dictated by the rate of the disc relative to walking/handlebar speed. Using this set-up, the relation between the handlebar speed and the disc speed can be systematically manipulated to provide different information to the two sensory systems.

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The main drawback of most of these types of treadmill systems is that they do not allow for combinations of purely linear and rotational movements, nor can they accommodate changes in walking direction. In order to address this problem, there have been a handful of attempts to develop omni-directional treadmills that allow limitless walking in every direction (Darken et al. 1997; Iwata 1999 (Torus treadmill)). The newest omni-directional treadmill built by the Cyberwalk project (http://www.cyberwalk-project.org) is the largest at 6.5 m (21’) x 6.5 m (4 m (13’) x 4 m walking area) and weighing 11 tonnes (See Figure 4). It is made up of a series of individual treadmill belts running in one direction (x) all mounted on two chains that move the belts in the orthogonal direction (y). Consequently, the combined motion of belts and chains can create motion in any direction. Again, this system is used in combination with a customized control algorithm to ensure that the walker remains centered on the platform while allowing them to change speed and direction (Souman et al. 2010).

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Another form of self-motion perception is that which occurs when one is passively moved through space. In this case, proprioceptive information about lower limb movements is not available and thus, in the absence of vision, self-motion is mainly detected through vestibular cues and other sources of non-visual information (e.g., wind, changes in skin pressure, vibrations, etc.). In order to understand how inertial information can be used for self-motion perception, researchers have used devices that are able to move an observer within 2D space, including manual wheelchairs (Allen et al. 2004; Waller and Greenauer 2007), programmable robotic wheelchairs (Berthoz, et al. 1995; Israël et al. 1997; Siegle et al. 2009), frictionless sleds (Seidman 2008), rotating platforms (Jürgens et al. 1999) and circular treadmills (Mittelstaedt and Mittelstaedt 1996; MPI circular treadmill, see Figure 3). Other devices allow for 3D movements such as standard 6-degree-of-freedom motion platforms (e.g. Stewart motion platform; Berger et al. 2010; Butler et al. 2010; Lehmann et al. 2008; Riecke et al. 2006; - http://www.cyberneum.com/MotionLab_en.html, See Figure 5). The MPI has recently developed a completely new type of motion simulator based on an anthropomorphic robot arm design (Teufel et al. 2007 - http://www.cyberneum.com/RoboLab_en.html, See Figure 6). The MPI Motion simulator can move participants linearly over a range of several meters and can rotate them around any axis, thus offering a high degree of freedom of motion. Observers can be passively moved along pre-defined trajectories (i.e. open loop; Siegle et al. 2009) or they can be given complete interactive control of their own movements (i.e. closed loop) via a variety of input devices, including a helicopter cyclic stick (Beykirch et al. 2007) and a steering wheel. As a consequence of its structure, certain degrees of freedom, such as roll and lateral arcs, do not interact with other degrees of freedom. Further, this serial design provides a larger workspace, allows for upside-down movements, infinite roll capabilities and continuous centrifugal forces; all of which are not possible with traditional simulator designs.

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In summary, as evidenced by the range of interfaces now available and customizable for addressing particular research questions, technology is now providing a means by which to carefully evaluate multimodal self-motion perception. Visualization devices can be used to assess how visual information alone can be used to perceive self-motion and can help to determine the importance of particular visual cues. Self-motion devices are allowing for the systematic isolation of vestibular or proprioceptive cues during both active, self-propelled movements and during passive transport. When these different interfaces are combined, this provides the opportunity to devise very specific multisensory scenarios. Much of this was not possible until very recently and as such, the field of multisensory self-motion perception is an exciting and newly emerging field.

3. The Influence of Visual, Proprioceptive and Vestibular information on Self-Motion Perception

3.1 Unisensory Self-Motion Perception

The classic approach to understanding how particular cues contribute to different aspects of self-motion perception has been to systematically eliminate particular cues and evaluate behaviors under reduced cue conditions. This, of course, is an important first step in understanding which cues are necessary and/or sufficient to accurately perceive self-motion. Performance has been measured for observers who only receive computer simulated visual information in the absence of body-based cues, and also when evaluating behaviors during movements in the complete absence of vision (e.g. when walking or being passively moved).

Much of the work on visual self-motion perception has looked specifically at the capacity of an observer to use optic flow alone to effectively perceive self-motion using either sparse visual input (i.e. textured ground plane or cloud of dots) or a rich visual scene (i.e. realistic visual environment). For example, it has been shown that individuals are relatively accurate at using dynamic visual information to discriminate and reproduce visually simulated traveled distances (Bremmer and Lappe 1999; Frenz et al. 2003; Frenz and Lappe 2005; Redlick et al. 2001; Sun et al. 2004a) and to update their landmark-relative position in space (Riecke et al. 2002). Other studies have shown that optic flow alone can be used to estimate various other characteristics of self-motion including, direction (Warren and Hannon 1988; Warren et al. 2001), and speed (Larish and Flach 1990; Sun et al. 2003) of self-motion through space. Optic flow can also induce postural sway in the absence of physical movement perturbations (Lee and Aronson 1974; Lestienne et al. 1977) and can be used to predict the time to contact with an environmental object (Lee 1976). Characteristics of visually-induced illusory self-motion, referred to as “vection”, have also received considerable interest, particularly by individuals using VR (Dichgans and Brandt 1978; Hettinger 2002; Howard 1986). Most readers have likely experienced vection while sitting in a stationary train when a neighbouring train begins to move. In this case, the global movement of the outside visual scene induces a compelling sense of self-motion when really it is the environment (i.e. the neighbouring train) that is moving relative to you. This phenomenon highlights the extent to which vision alone can create a compelling illusion of self-motion.

Others have studied conditions in which access to visual information is removed and only body-based cues (e.g., inertial and proprioceptive cues) remain available during movement. It has been clearly established that humans are able to view a static target up to 20m and accurately reproduce this distance by walking an equal extent without vision (Elliott 1986; Fukusima et al. 1997; Loomis et al. 1992; Mittelstaedt and Mittelstaedt 2001; Rieser et al. 1990; Sun et al. 2004b; Thomson 1983). Participants can also continuously point to a previously viewed target when walking past it blindfolded on a straight, forward trajectory (Campos et al. 2009; Loomis et al. 1992). Others have demonstrated that individuals are able to estimate distance information when learning and responding through blindfolded walking (Ellard and Shaughnessy 2003; Klatzky et al. 1998; Mittelstaedt and Mittelstaedt, 2001; Sun et al. 2004b). A recent paper by Durgin et al. (2009) looked specifically at the mechanisms through which proprioceptive information can be used to estimate an extent of self-motion and suggest that step integration might be a form of odometry used by humans (even when explicit step counting is not permitted). Such mechanisms are similar to those previously shown to be used by terrestrial insects such as desert ants (Wittlinger et al. 2006). There is some evidence, however, that step integration could be susceptible to accumulating noise and might therefore only be reliable for short traveled distances (Cheung et al. 2007)

A thorough collection of research has focused specifically on investigating the role of inertial information, mainly provided through the vestibular organs, during simple linear and rotational movements (Berthoz et al. 1995; Bertin and Berthoz 2004; Butler et al. 2010; Harris et al. 2000; Israël and Berthoz 1989; Ivanenko et al. 1997; Mittelstaedt and Glasauer 1991; Mittelstaedt and Mittelstaedt 2001; Seidman 2008; Siegle et al. 2009; Yong et al. 2007) and when traveling along more complex routes involving several different segments (Allen et al.

2004; Sholl et al. 1989; Waller and Greenauer 2007). Some findings have been interpreted to indicate that head velocity and displacement can be accurately perceived by temporally integrating the linear acceleration information detected by the otolith system. Others indicate that the influence and/or effectiveness of vestibular information is somewhat limited; particularly when other non-visual information such as vibrations are no longer available (Seidman 2008), when moving along trajectories with more complex velocity profiles (Siegle et al. 2009), or during larger scale navigation (Waller and Greenauer 2007).

3.2 Multisensory Self-Motion Perception

As important as it is to understand how humans are able to perceive self-motion during reduced sensory conditions, under most natural conditions, it is almost always the case that information from several modalities is concurrently available. Unlike other types of cue combinations that maintain a correlational relationship, in the case of self-motion perception, visual-proprioceptive and proprioceptive-vestibular interactions are often casually related. For instance, when an observer self-propels themselves during walking, they immediately experience changes in optic flow information as a direct consequence of their movement. Rarely does the entire visual field move when the body signals that it is stationary or vice versa. In fact, motion sickness often arises when the brain attempts to reconcile the fact that the visual environment (e.g. the interior cabin of a ship) does not appear to move relative to the head and yet the vestibular system is clearly detecting physical movements.

Traditionally, several different approaches have been used to evaluate the contributions of particular sensory systems to self-motion perception and spatial updating during egocentric movements. These have included: a) directly comparing the effects of multisensory versus unisensory conditions (most common approach); b) creating subtle and transient cue conflicts between the information provided by different sensory systems; and c) introducing a prolonged conflict as a way of evaluating the effects of sensory recalibration. Empirical evidence obtained using each of these strategies will be discussed in turn, with a focus on studies that have exploited simulation tools and techniques.

3.2.1 Effects of Cue Combination

Tasks that have been used to investigate the role of different sensory systems for self-motion perception have ranged from estimating the speed, distance, and direction of a simple linear or rotational movement, returning to origin after traveling a two segment path separated by a turn, and navigating longer, more complex routes. In order to evaluate the contributions of particular sensory systems to each of these tasks, research has directly compared reduced cue conditions to conditions in which all or most sensory information is available. What is clear is that no one sensory system appears to be globally critical for all aspects of self-motion perception, but rather, the relative importance of particular modalities is somewhat task dependent. While an exhaustive review is not provided here, this summary is intended to emphasize the necessity of taking a comprehensive approach to evaluating multisensory self-motion perception as it applies to different levels and types of behaviors.

When looking at multisensory self-motion for purely rotational movements, several studies have indicated that proprioceptive information appears to be quite important. For instance, Bakker et al. (1999) asked subjects to turn various angles while in a virtual forest. They compared conditions in which only visual or vestibular (passive rotations) information was available, to conditions in which participants actively rotated themselves by moving their legs. It was reported that having only visual information led to the poorest performance in this task, followed by pure vestibular stimulation. When participants actually moved themselves they were the most consistent and accurate. Visual information, however, was not completely ignored, because the estimates in the combined cue condition (i.e. when participants saw the forest while physically moving), fell between the two unisensory conditions, indicating a combined cue effect. Lathrop and Kaiser (2002) also evaluated perceived self-orientation by measuring pointing accuracy to unseen virtual landmarks. Performances in which participants learned the location of landmarks (via a HMD) during full-body rotations were better than when the same movements were simulated visually on a desktop monitor.

Consistent with the idea that pure vestibular inputs are not sufficient for self-orientation in space during rotational movements, Wilkie and Wann (2005) reported that, when completing steering maneuvers by rotating on a motorized chair, inertial information did not contribute significantly more than that already provided through various visual inputs. Using both a realistic, visually rich scene and a pure optic flow stimulus, Riecke et al. (2006) evaluated the effects of rotational inertial cues on obligatory egocentric spatial updating. It was found that neither in rich, nor impoverished visual conditions did the added inertial information improve performance. Unlike other studies, however, Riecke et al. (2006) demonstrated that with a realistic, familiar visual scene, dynamic visual information alone could be used for updating egocentric positions.

Lehmann, et al. (2008) evaluated the benefits of having inertially-based self-motion information during the mental rotation of an array of objects. In this case, participants were seated on a motion simulator while viewing a large projection screen and a virtual array of objects displayed on a table top directly in front of them. When having to identify which object in the array was shifted after a viewpoint change (either physically or visually introduced), a detection advantage was observed after the physical rotation. This indicates that the inertial information provided during the rotation facilitated mental rotation, thus also supporting previous real-world studies (Simons and Wang 1998).

Others have also investigated individual cue contributions during purely linear movements. For instance, Harris et al. (2000) evaluated the ability of participants to estimate linear trajectories using either visual information provided through a HMD and/or vestibular sources when passively moved on a cart. Here they found that when visual and vestibular inputs were concurrently available, estimates more closely approximated those of the purely vestibular estimates than the purely visual estimates. The importance of body-based cues for traveled distance estimation has also been revealed through a series of studies by Campos et al. (2007b). In these experiments body-based cues were provided either by: a) natural walking in a fully-tracked free walking space (proprioceptive and vestibular); b) being passively moved by a robotic wheelchair (vestibular); or c) walking in place on a treadmill (proprioceptive). Distances were either presented through optic flow alone, body-based cues alone, or both visual and body-based cues combined. In this case, combined cue effects were again always observed, indicating that no modality was ever completely disregarded. When visual and body-based cues were combined during walking, estimates more closely approximated the unisensory body-based estimates. When visual and inertial cues were combined during passive movements, the estimates fell in between the two unisensory estimates.

Sun et al. (2004a) investigated the relative contributions of visual and proprioceptive information by having participants compare two traveled distances experienced by riding a stationary bicycle down a virtual hallway viewed in a HMD. It was concluded in this case that visual information was predominantly used. It is important to note, that when riding a bike there is no absolute one-to-one relationship between the metrics of visual space and those of the proprioceptive movements because of the unknown scale of one pedal rotation (i.e. this would be depend on the gear, for instance). Even under such conditions, combined cue effects were observed, such that, when visual and proprioceptive were both available, estimates differed from those in either of the unimodal conditions.

Cue combination effects have also been evaluated for speed perception during linear self-motion (Durgin et al. 2005; Sun et al. 2003). For instance, Durgin et al. (2005) have reported that physically moving (i.e. walking or being passively moved) during visually-simulated self-motion causes a reduction in perceived visual speed compared to situations in which visually-simulated self-motion is experienced when standing stationary. The authors attribute this to the brain's attempt at optimizing its efficiency when presented with two, typically correlated cues with a predictable relationship.

Slightly more complex paths consisting of two linear segments separated by a rotation of varying angles have also been used to understand how self-motion is integrated across different types of movements. Typically, such tasks are used to answer questions about how accurately an observer is able to continuously update their position in space without using landmarks (i.e. perform path integration). For instance, triangle completion tasks typically require participants to travel a linear path, rotate a particular angle, travel a second linear path and then return to home (or face the point of origin). In a classic triangle completion study, Klatzky et al. (1998) demonstrated that during purely visual simulations of rotational components of the movement (i.e. the turn), participants were highly disoriented when attempting to face back to start compared to conditions under which full-body information was present during the rotation. In fact, the physical turn condition resulted in errors that were almost as low as the errors in the full, real walking condition in which body information was available during the entire route (walk, turn, walk, face start). Unlike several of the rotational self-motion experiments described above, vestibular inputs during the rotational component of this triangle completion task appeared to be very important for perceived self-orientation. Again, however, it emphasizes the importance of physical movement cues over visual cues in isolation.

Using a similar task, Kearns et al. (2002), demonstrated that pure optic flow information was sufficient to complete a return-to-origin task, although the introduction of body-based cues (proprioceptive and vestibular) when walking through the virtual environment led to decreased variability in responding. This was true irrespective of the amount of optic flow that was available from the surrounding environment, thus suggesting a stronger reliance on body-based cues. When using a two-segment path reproduction task to compare moving via a joystick versus walking on the Torus treadmill, Iwata and Yoshida (1999) reported a higher accuracy during actual walking on the treadmill compared to when active control of self-motion was provided through the use of an input device.

Chance et al. (1998) used a more demanding task in which participants were asked to travel through a virtual maze and learn the locations of several objects as they moved. At the end of the route, when prompted, participants turned and faced the direction of a particular target. Here the authors compared conditions in which participants actually walked through the maze (proprioceptive and vestibular inputs during translation and rotation), to that in which a joystick was used to navigate the whole maze (vision alone), to that in which a joystick was used to translate and physical rotations were provided (proprioceptive and vestibular inputs during rotation only). When physically walking errors were the lowest, when only visual information was available errors were the highest, and when only physical rotations were possible, responses fell in between (although they were not significantly different from the vision only condition).

Using similar conditions Ruddle and Lessels (2006; 2009) observed a comparable pattern of results when evaluating performances on a search task in a room-sized virtual environment. Specifically, conditions in which participants freely walked during their search resulted in highly accurate and efficient search performance, when only allowed to physically rotate observers were less efficient, and even less efficient with only visual information.

Waller and colleagues have evaluated questions related to multisensory navigation as they relate to larger-scale self-motion perception and the acquisition and encoding of spatial representations. For instance, they have considered whether the inertial information provided during passive movements in a car contributes to the development of an accurate representation of a route beyond the information already provided through dynamic visual inputs (Waller et al. 2003). They found that inertial inputs did not significantly improve performance and even when the inertial cues were not consistent with the visuals, instead of disorienting or distracting observers, there was in fact no impact on spatial memory. Similarly, Waller and Greenauer (2007) asked participants to travel along a long indoor route (around 480 feet) and then evaluated their ability to perform a variety of spatial tasks. Although participants learned the route under different sensory conditions including, by walking with updated vision, by being passively moved with updated vision, or by viewing a visual simulation of the same movement, there appeared to be no significant effects of cue availability (Although see Waller et al., 2004). Overall, the less obvious role of body-based cues in these larger-scale, more cognitively demanding tasks stands in contrast to the importance of body-based cues evidenced in simpler self-motion updating tasks. As such, future work must help to reconcile these findings and to form a more comprehensive model of multisensory self-motion in order to understand how the scale of a space, the accumulation of self-motion information, and the demands of the task relate to relative cue-weighting.

Not only do the effects of cue combinations exhibit themselves through consciously produced behaviors or responses in spatial tasks, but they can also be seen in other aspects of self-motion, including the characteristics of gait. For instance, Mohler et al. (2007a) investigated differences in gait parameters such as walking speed, step length and head-to-trunk angle when walking with eyes open versus closed and also when walking in a VE (wearing an HMD) versus walking in the real world. It was found that participants walked slower and exhibited a shorter stride length when walking with their eyes closed. During sighted walking while viewing the VE through the HMD, participants walked slower and took smaller steps than when walking in the real world. Their head-to-trunk angle was also smaller when walking in the VE, most likely due to the reduced vertical FOV.

Similarly, Sheik-Nainar and Kaber (2007) evaluated different aspects of gait, such as speed, cadence, and joint angles when walking on a treadmill. They evaluated the effects of presenting participants with congruent and updated visuals (via a HMD projecting a simulated version of the lab space) compared to stationary visuals (real world lab space with reduced FOV to approximate HMD). These two conditions were compared to natural, overground walking. Results indicated that while both the treadmill conditions caused participants to walk slower and take smaller steps, when optic flow was consistent with the walking speed, gait characteristics more closely approximated that of overground walking.

Finally, although most of the work on multisensory self-motion perception has dealt specifically with visual interactions with body-based cues, it is important to note that researchers have begun to evaluate the impact of auditory cues on self-motion perception. For instance, Valjamae et al (2008) have shown that sounds associated with self-motion through space, such as footsteps, can enhance the perception of linear vection. Further, Riecke et al (2009) have shown that sounds produced by a particular spatial location (i.e. by water flowing in a fountain) can enhance circular vection when appropriately updated with the moving visuals.

3.2.2 Cue weighting under conflict conditions

While understanding the perceptual and behavioral consequences of adding or subtracting cues remains an informative approach to understanding self-motion perception, it is limited when attempting to precisely quantify the contributions made by individual cues or when defining the exact principles underlying this integration. Considering that individual modalities are sufficient in isolation for many of the different self-motion based tasks, it is difficult to assess how the different modalities combine when several are simultaneously present. In most cases, the information provided by two different sensory modalities regarding the same external stimuli is redundant and thus, it is difficult to dissociate the individual contributions of each.

A popular and effective strategy for dissociating naturally congruent cues has been the cue conflict approach. This approach involves providing individual modalities with different and incongruent information about a single perceptual event or environmental stimuli. Much of the classic research using experimentally derived cue conflicts in the real world comes from work using displacement prisms (Pick et al. 1969; Welch and Warren 1980), and other recent examples have used magnification/minimization lenses (Campos et al. 2010). In the case of self-motion perception, prism goggles have been used, for instance, to shift the entire optic array horizontally, thus causing a conflict between what is perceived visually and what is perceived via other modalities such as proprioception (Rushton et al. 1999). While prism approaches have, in the past provided great insight into sensory-motor interactions in the real world, distortions can occur and the type of conflict manipulations that can be introduced are limited (e.g. restricted to changing heading direction or vertical eye-height). VR, however, provides a much more flexible system that can change many different characteristics of the visual environment as well as present visual speeds, traveled distances, heading directions, orientation in 3D space, etc. that differ from that being simultaneously presented to proprioceptive and vestibular sources. In the context of understanding multisensory integration during self-motion, cue conflicts have been used to understand a) the immediate consequences of transient sensory conflict (momentary incongruencies) and b) the recalibration of optic flow and body-based cues over time (enduring conflict). Here each will be considered.

In the case of transient cue conflicts, it is typically the case that such conflicts occur on a trial-by-trial basis in an effort to avoid adaptation effects. In this case, the idea is ultimately to understand the relative cue-weighting of visual and body-based cues when combined under normal circumstances. For instance, Sun et al. (2003, 2004a) used this strategy in the aforementioned simulated bike riding experiment as a way of dissociating the proprioceptive information provided by pedaling, from the yoked optic flow information provided via an HMD. In a traveled distance comparison task they reported an overall higher weighting of visual information when the relation between the two cues was constantly varied. However, the presence of proprioceptive information continued to improve visually-specified distance estimates, even when it was not congruent with the visuals (Sun et al. 2004a). On the other hand, Harris et al. (2000) used a similar technique to examine the relative contributions of visual-vestibular information to linear self-motion estimation over several meters and found that observers' estimated more closely approximated the distances specified by vestibular cues than those specified by optic flow. Sun et al. (2003) also evaluated the relative contributions of visual and proprioceptive information using a speed discrimination task while bike riding down a virtual hallway. Here, they found that although both cues contributed to speed estimates, proprioceptive information was in fact weighted higher.

For smaller scale, simulated full-body movements have also investigated visual-vestibular integration by presenting optic flow stimuli via a projection screen and presenting vestibular information via a 6-degree-of-freedom motion platform (Butler et al. 2010; Fetsch et al. 2009; Gu et al. 2008). In this case, it has consistently been shown that the variances observed for the estimates in the combined cue conditions are lower than estimates in either of the unisensory conditions. In the series of traveled distance experiments by Campos et al. described above (2007b), subtle cue conflicts were also created between visual and body-based cues (see also Kearns 2003). Here incongruencies were created by either changing the visual gain during physical movements or changing the proprioceptive gain during walking (i.e. by changing the treadmill speed). Overall, the results demonstrated a higher weighting of body-based cues during natural overground walking, a higher weighting of proprioceptive information during treadmill walking, and a relatively equal weighting of visual and vestibular cues during passive movement. These results were further strengthened by the fact that the higher weighting of body-based cues during walking was unaffected by whether visual or proprioceptive gain was manipulated.

The vast majority of the work evaluating relative cue-weighting during self-motion perception using cue conflict paradigms has considered how vision combines with different body-based cues. Others have recently conducted some of the first experiments to use this technique for studying proprioceptive-vestibular integration. In order to achieve this, they used the MPI circular treadmill setup described above (See Figure 3). Because this treadmill setup consists of a handlebar that can move independently of the treadmill disc, the relation between the handlebar speed and the disc speed can be changed to provide different information to the two sensory systems

Cue conflict techniques have also been used to evaluate the effect of changing cue relations on various gait parameters. For instance, Prokop et al. (1997) asked participants to walk at a comfortable, yet constant speed on a self-driven treadmill. When optic flow was accelerated or decelerated relative to the actual walking speed, unintentional modulations in walking speed were observed. Specifically, when the visual speed increased, walking speeds decreased, while the opposite was true for decreased visual speeds. Similarly, it has also been shown that walk-to-run and run-to-walk transitions can also be unintentionally modified by providing a walking observer with different rates of optic flow (Guerin and Bardy 2008; Mohler et al. 2007b). Again, as the rate of optic flow is increased, the speed at which an observer will transition from running to walking will be lower, while the opposite is true for decreased optic flow rates.

Another group of studies has used prolonged cue conflicts as a way of investigating sensory-motor recalibration effects during self-motion. A classic, real-world multisensory recalibration experiment was conducted by Rieser and colleagues (1995), in which an extended mismatch was created between visual flow and body-based cues. Using a cleverly developed set-up, participants walked on a treadmill at one speed, while it was pulled behind a tractor moving at either a faster or slower speed. Consequently, the speed of the movement experienced motorically was either greater or less than the speed of the visually experienced movement. Following adaptation, participants walked blindfolded to previewed visual targets. Results indicated that when the visual flow was slower than the locomotor information participants overshot the target (relative to pre-test), whereas when the visual flow was faster than the locomotor information they undershot the target distance.

While the approach used by Rieser et al. (1995) was ingenious, one can imagine that this strategy can be accomplished much more easily, safely and under more highly-controlled circumstances by using simulation devices. Indeed, the results of Rieser et al.'s (1995) original study have since been replicated and expanded upon using VR. This has been achieved by having participants walk on a treadmill or within a tracked walking space while they experience either relatively faster or slower visually perceived flow via a head-mounted display or a large FOV projection display (Durgin et al. 2005; Mohler et al. 2007c; Proffitt et al. 2003; Thompson et al. 2005). For instance, it has been shown that adaptations that occur when walking through a VE on a treadmill transfer to a real-world blind walking task (Mohler et al., 2007c). There is also some indication that the aftereffects observed during walking on solid ground (tracked walking space) are larger than those observed during treadmill walking (Durgin et al. 2005). Pick et al. (1999) have also shown similar recalibration effects for rotational self-motion.

3.3 Unique challenges in studying multisensory self-motion perception

In recent years, much of the multisensory research community have used psychophysical methods as a way of evaluating whether two cues are integrated in a statistically optimal fashion (i.e. Maximum likelihood estimation (MLE) or Bayesian approaches to cue integration; Alais and Burr 2004; Blake and Bülthoff 1993; Bülthoff and Mallot 1988; Bülthoff and Yuille 1991, 1996; Butler et al. 2010; Cheng et al. 2007; Ernst and Banks 2002; Ernst and Bülthoff 2004; Fetsch et al. 2009; Knill and Saunders 2003; Kording and Wolpert 2004; MacNeilage et al. 2007; Welchman et al. 2008). A traditional design used to evaluate such predictions involves a comparison of the characteristics of the psychometric functions (i.e. just noticeable difference or variance scores) obtained during unisensory conditions to those obtained during multisensory conditions. Based on the assumptions of an MLE account, at least two general predictions can be made. First, the variance observed in the combined sensory condition should be lower than that observed in either of the unimodal conditions. Second, the cue with the highest unimodal variance should be given less weight when the two cues are combined. A cue conflict is often used as a way of providing slightly different information to each of the two cues as a way of identifying which cue was weighted higher in the combined estimate.

However, because of the tight relationship between visual, vestibular and proprioceptive information during self-motion, this presents a unique challenge for obtaining unbiased unisensory estimates through which to base predictive models. This is due to the fact that, even in the unisensory conditions, there remains an inherent conflict. For instance, when visual self-motion is simulated in the absence of proprioceptive and vestibular inputs, this could be a challenge for the brain to reconcile. Because the proprioceptive and vestibular systems cannot be “turned-off”, they constantly send the brain information about self-motion; whether that information indicates self-motion through space or a stationary egocentric position. Therefore, when the visual system is provided with a compelling sense of self-motion, both the muscles and joints and inner ear organs clearly do not support this assessment.

Despite these constraints, effective models of self-motion perception have recently been developed as a way of assessing some of the abovementioned predictions (e.g. Jürgens and Becker 2006; Laurens and Droulez 2007). For instance, Jürgens and Becker (2006) evaluated the weighting of vestibular, proprioceptive and cognitive inputs on displacement perception. They report that the more sensory information that is available, the less participants appeared to rely on cognitive strategies. In addition, with increasing sources of combined information, lower variance scores were observed. Cheng et al. (2007) have also summarized some of the multisensory work in locomotion and spatial navigation and evaluated how these findings fit within the context of Bayesian theoretical predictions. Overall, there remains much important work to be done concerning the development of quantitative models describing the principles underlying multisensory self-motion perception.

4. Advantages and disadvantages of using simulation technology to study multisensory self-motion perception

Throughout this chapter numerous unique benefits of using visually simulated environments and various self-motion simulators to study multisensory self-motion perception have been described. However, because VR technology is not yet capable of achieving the extraordinary task of capturing every aspect of reality in veridical spatial and temporal terms, there are several limitations that must also be acknowledged. Below we will briefly consider some of the additional advantages and disadvantages of using VR to studying multisensory self-motion perception not already discussed earlier in this chapter (see also Bülthoff and van Veen 2001; Loomis et al. 1999; Tarr and Warren 2002).

Considering that the natural world contains an infinite amount of contextual and behaviorally relevant sensory information, it is often difficult to predict how these sources of information will interact. As mentioned above, perhaps the most significant advantage of VR is that it can it provide a highly controlled, multisensory experience. It is also able to overcome some of the difficulties inherent in experimentally manipulating a unimodal component of a multisensory experience and for dissociating individual cues within one modality. Moreover, each of these manipulations is achieved under safe, low risk, highly replicable circumstances and often (although not always) at a much lower cost than is possible in the real world. For instance, Souman et al. (2009) were interested in empirically testing the much-speculated question of whether humans indeed walk in circles when lost in the desert. To do this, Souman and colleagues traveled to the Sahara desert. Without going through this level of effort and expense, conducting such experiments would otherwise be extremely difficult to test in the real world because of the need to have a completely sparse environment through which an individual can walk for hours. However, following the original, real world experiment, Souman and colleagues have since been able to evaluate similar questions under more precise conditions by using the newly developed MPI omni-directional treadmill. Here they can manipulate particular characteristics of the VE as a way of evaluating the exact causes of any observed veering behaviors, while still allowing for limitless walking capabilities in any direction.

While many of the tasks described thus far have dealt mainly with consciously reported or reproduced behaviors in VEs, it is also important to note that even unconscious, physiological reactions (e.g. heart rate and galvanic skin response) often respond in ways similar to that observed for real world events. For instance, when having observers walk to the very edge of cliff in a VE, not only do many participants report a compelling sense of fear, but their heart rate also increases considerably (Meehan et al. 2005). This effect is further amplified when additional sensory cues, such as the haptic sensation of feeling the edge of drop-off with one's feet are also provided.

The disadvantages of VR must also be accounted for when considering whether particular technologies are appropriate for addressing specific research questions. For instance, as mentioned above, there is often a trade-off between high quality, wide FOV visualization systems, and mobility. However, the impact that a reduced FOV has on self-motion perception is still relatively unclear. The results of Warren and Kurtz (1992) indicate that, unlike previously believed, peripheral optic flow information is not necessarily the dominant source of visual input when performing a visual heading task, but rather, central visual input tends to provide more accurate estimates. Banton et al. (2005) on the other hand indicate that peripheral information seems to be important for accurately perceiving visual speed when walking. Therefore, the perceptual impact of having a restricted FOV on the perception of various aspects of self-motion requires further investigation.

There are also several clear and consistent perceptual errors that occur in VEs that do not occur in the real world. For instance, while much research has now demonstrated that humans are very good at estimating the distance between themselves and a stationary target in the real world (see Loomis and Philbeck 2008 for a review), the same distance magnitudes are consistently underestimated in immersive VEs by as much 50% (Knapp and Loomis 2004; Loomis and Knapp 2003; Thompson et al. 2004; Witmer and Kline 1998). This effect is not entirely attributable to poor visual graphics (Thompson et al. 2004) and while some have reported a distance compression effect when the FOV is reduced and the viewer is stationary (Witmer and Kline 1998), others have shown that when head movements are allowed under restricted FOV conditions, these effects are not observed (Creem-Regehr et al. 2005; Knapp and Loomis 2004). Strategies have been used to reduce this distance compression effect, for instance, by providing various forms of feedback when interacting in the VE (Mohler et al. 2007c; Richardson and Waller 2005; Waller and Richardson 2008), yet the exact cause of this distance compression remains unknown.

Another, less studied perceptual difference between virtual and real environments that has also been reported, is the misperception of visual speed when walking in VEs (Banton et al. 2005; Durgin et al. 2005). For instance, Banton et al. (2005) required participants to match their visual speed (presented via an HMD) to their walking speed as they walked on a treadmill. When facing forwards during walking, visual speeds were increased by about 1.6x that of the walking speed in order to appear equal.

When motion tracking is used to visually update an observer’s position in the VE, there is also the concern that temporal lag has the potential to create unintentional sensory conflict, disrupt the feeling of presence, and cause cyber-sickness. There is also some indication that characteristics of gait change when walking overground in a VE compared to the real world (Mohler et al. 2007a), and walking on a treadmill in a VE is associated with increased stride frequency (Sheik-Nainar and Kaber 2007). It is yet unknown how such changes in physical movement characteristics might impact particular aspects of self-motion perception.

In addition to lower-level perceptual limitations of VEs, there are also higher-level cognitive effects that can affect behavior. For instance, there is often a general awareness when interacting within a VE that one is in fact engaging with artificially derived stimuli. Observers might react differently to simulated scenarios, for instance, by placing a lower weighting on sensory information that they know to be simulated. Further, when visually or passively presented movements defy what is physically possible in the real world, this information might also be treated differently. In cue conflict situations, it has also been shown that relative cue weighting during self-motion can change as a function of whether an observer is consciously aware of any cue conflicts that are introduced (Berger and Bülthoff 2009).

There is also a discord between the perceptual attributes of the virtual world that an observer is immersed in and the knowledge of the real world that they are physically located within. Evidence that this awareness might impact behavior comes from findings indicating that, during a homing task in a VE, knowledge of the size of the real world room impacts navigational behaviors in the VE (Nico et al. 2002). Specifically, when participants knowingly moved within in a smaller real world room they undershot the origin in the VE compared to when they were moving within a larger real world space (even though the VEs were of identical size).

Overall, researchers should ideally strive to exploit the advantages offered by the various available interfaces while controlling for the specific limitations through the use of others. Further, whenever possible, it is best to take the reciprocally informative approach of comparing and coordinating research conducted in VR with that taking place in real world testing scenarios.

5. Multisensory self-motion perception: An applied perspective

Being able to effectively and accurately represent multiple sources of sensory information within a simulated scenario is essential for a broad variety of applied areas. VR technologies are now being widely adopted for use in areas as diverse as surgical, aviation and rescue training, architectural design, driving and flight simulation, athletic training and evaluation, psychotherapy, gaming and entertainment. Therefore, not only is it important to understand cue-integration during relatively simple tasks, but it is also imperative to understand these perception-action loops during more complex, realistic, multi-faceted behaviors. While most multisensory research has focused on the interaction of only two sensory cues, most behaviors occur in the context of a variety of sensory inputs and therefore understanding the interaction of three or more cues (e.g. Bresciani et al. 2008) during ecologically valid stimulus conditions is also important. These issues are particularly critical considering the possibly grave consequences of misperceiving spatial properties or incorrectly adapting to particular stimulus conditions. Here we briefly consider two applied fields that we feel are of particular interest as they relate to multisensory self-motion perception; helicopter flight behavior and locomotor rehabilitation.

Helicopter flight represents one of the most challenging multisensory control tasks accomplished by humans. The basic science of helicopter flight behavior is extremely complex and the effects of specific flight simulation training on real world performance (i.e. transfer of training) remain poorly understood. Because several misperceptions are known to occur during helicopter flight, it is important to first understand the possible causes of such misperceptions in a way that will allow for more effective training procedures. One example of such a misperception that can occur when reliable visual information is not available during flight is the somatogravic illusion. In this case, the inertial forces during accelerations of the aircraft and those specifying gravitational forces may become confused, thus causing an illusion of tilt during purely linear accelerations, often resulting in devastating outcomes.

Several studies have been conducted using the MPI Motion Simulator by outfitting it with a helicopter cyclic stick and various visualization devices in order to create a unique and customizable flight simulator. For instance, non-expert participants were trained on the simulator to acquire the skills required to stabilize a helicopter during a hovering task (Nusseck et al. 2008). In this case, the robot was programmed to move in a way that mimicked particular helicopter dynamics and the participants' task was to hover in front of real world targets. Two helicopter sizes were simulated; one that was light and agile and another that was heavy and inert. Participants were initially trained on one of the two helicopters and subsequently their performance was tested when flying the second helicopter. This method was used to reveal the novice "pilots" ability to transfer the general flight skills they learned on one system, to another system with different dynamics. The results indicated that participants were able to effectively transfer the skills obtained when training in the light helicopter to the heavy helicopter, while the opposite was not true. Understanding these transfer of training effects are important for assessing the effectiveness of both, training in simulators and flying in actual aircraft and also for understanding the subtle differences of flying familiar versus unfamiliar aircraft; something almost all pilots are at one time faced with.

Another applied area that would benefit greatly from understanding multisensory self-motion perception is the diagnosis and rehabilitative treatment of those with disabling injury or illness. A significant percentage of the population suffers from the locomotor consequences of Parkinson's disease, stroke, acquired brain injuries and other age-related conditions. Often times rehabilitation therapies consist of passive range of motion tasks (through therapist manipulation or via robotic assisted walking), or self-initiated repetitive action tasks. In the case of lower-limb sensory-motor disabilities, one rehabilitative technique is to have patients walk on a treadmill as a way of actively facilitating and promoting the movements required for locomotion. The focus of such techniques, however, is on the motor system exclusively, with very little consideration given to the multi-modal nature of locomotion. In fact, treadmill walking actually causes a conflict between proprioceptive information, which specifies that the person is moving, and visual information, which indicates a complete lack of self-motion.

Considering that one of the key factors in the successful learning or relearning of motor behaviors is feedback, a natural source of feedback can be provided by the visual flow information obtained during walking. As such, incorporating visual feedback into rehabilitative treadmill walking therapies could prove to be of great importance. Actively moving within a VE is also likely to be highly rewarding for individuals lacking stable mobility and thus may increase levels of motivation in addition to recalibrating the perceptual-motor information.

While some work has been done to evaluate multi-modal effects in upper-limb movement recovery, this is not something that has been investigated as thoroughly for full body locomotor behavior such as walking. A group that has evaluated such questions is Fung et al. (2006) who have used a self-paced treadmill, mounted on a small motion platform coupled with a projection display as a way of adapting gait behavior in stroke patients. They found that, by training with this multimodal system, patients showed clear locomotor improvements such as increases in gait speed and the ability to more flexibly adapt their gait when faced with changes in ground terrain. Rehabilitation research and treatment programs can benefit greatly from the flexibility, safety, and high level of control offered by VR and simulator systems. As such, technologies that offer multimodal stimulation and control are expected to have a major impact in the future (for example see, Toronto Rehabilitation Institute's Challenging Environment Assessment Laboratory (CEAL); http://www.cealidapt.com)

6. Summary

This chapter has emphasized the closed-loop nature of human locomotor behavior by evaluating studies that preserve the coupling between perception and action during self-motion perception. This combined cue approach to understanding full body movements through space offers unique insights into multisensory processes as they occur over space and time. Future work in this area should aim to define the principles underlying human perceptual and cognitive processes in the context of realistic sensory information. Using simulation techniques also allows for a reciprocally informative approach of using VR as a useful tool for understanding basic science questions related to the human observer in action, while also utilizing the results of this research to provide informed methods of improving VR technologies. As such, the crosstalk between applied fields and basic science research approaches should be strongly encouraged and facilitated.

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Figure Captions

Figure 1: ***MPI Panoramic projection screen.*** This large, spherical panoramic projection screen consists of four projectors that project images of Virtual Environments (VEs) onto the surrounding curved walls and also the floor. This provides a field of view of more than 220 degrees horizontal and 125 degrees vertical, thereby taking up almost the entire human visual field. Participants can move through the VE via various different input devices such as bicycles, driving interfaces, or joysticks (as is shown here). The VE displayed in the photo is a highly realistic virtual model of the city center of Tübingen.
Photo courtesy of: Axel Griesch

Figure 2: ***MPI Tracking Laboratory***. This fully tracked, free-walking space is 12×12 meters in size. In this space, participants' position and orientation is tracked using an optical tracking system (16 Vicon MX13 cameras) through the monitoring of reflective markers. Information about a participant's position and orientation is sent from the optical trackers, via a wireless connection, to a backpack-mounted laptop worn by the participant. This system can therefore be used to both update the visual environment as a function of participants' own movements (i.e. in the HMD as shown here) and to capture different movement parameters. With this setup it is also possible to track two or more observers and thus allows for multi-user interactions within a VE.
Photo courtesy of: Manfred Zentsch

Figure 3: ***MPI Circular Treadmill***. This circular treadmill (3.6 m in diameter) allows for natural, full-stride walking in circles. It is equipped with a motorized handlebar that can move independently from the treadmill belt/disc. Using this set-up, the relation between the handlebar speed and the disc speed can be systematically manipulated to provide different information to the two sensory systems. A computer monitor mounted on the handlebar can also be used to present visual information during movement.
Photo courtesy of: Axel Griesch

Figure 4: ***Cyberwalk Omni-directional Treadmill***. This large omni-directional treadmill was built by the Cyberwalk project (http://www.cyberwalk-project.org) and is located at the MPI for Biological Cybernetics. It is 6.5 m x 6.5 m (4 m x 4 m walking area) and weighs 11 tonnes. It is made up of a series of individual treadmill belts running in one direction (x) all mounted on two chains that can move the belts in the orthogonal direction (y). Consequently, the combined motion of belts and chains can create motion in any direction.
Photo courtesy of: Tina Weidgans

Figure 5: ***MPI Stewart motion platform***. The Motion Lab at the MPI for Biological Cybernetics consists of a Maxcue 600, six degree-of-freedom Stewart platform coupled with a 86 × 65 degree field of view projection screen that is mounted on the platform. Subwoofers are installed underneath the seat to produce somotosensory vibrations as a way of masking the platform motors. Movements can be presented passively, or participants can control the platform via several different input devices including a helicopter cyclic stick and a 4 degree-of-freedom haptics manipulator.
Photo courtesy of: Manfred Zentsch

Figure 6: ***MPI Motion Simulator***. The MPI Motion simulator is based on an anthropomorphic robot arm design and can move participants linearly over a range of several meters and can rotate them around any axis. Observers can be passively moved along pre-defined trajectories or they can be given complete interactive control of their own movements via a variety of input devices, such as a helicopter cyclic stick or a steering wheel. A curved projection screen can also be mounted on the end of the robot arm in front of the seated observer or alternatively an HMD can be used to present immersive visuals. Optical tracking systems have also been mounted on the robot arm in order to measure the position and orientation of an observer’s head or their arm during pointing-based tasks.
Photo courtesy of: Anne Faden


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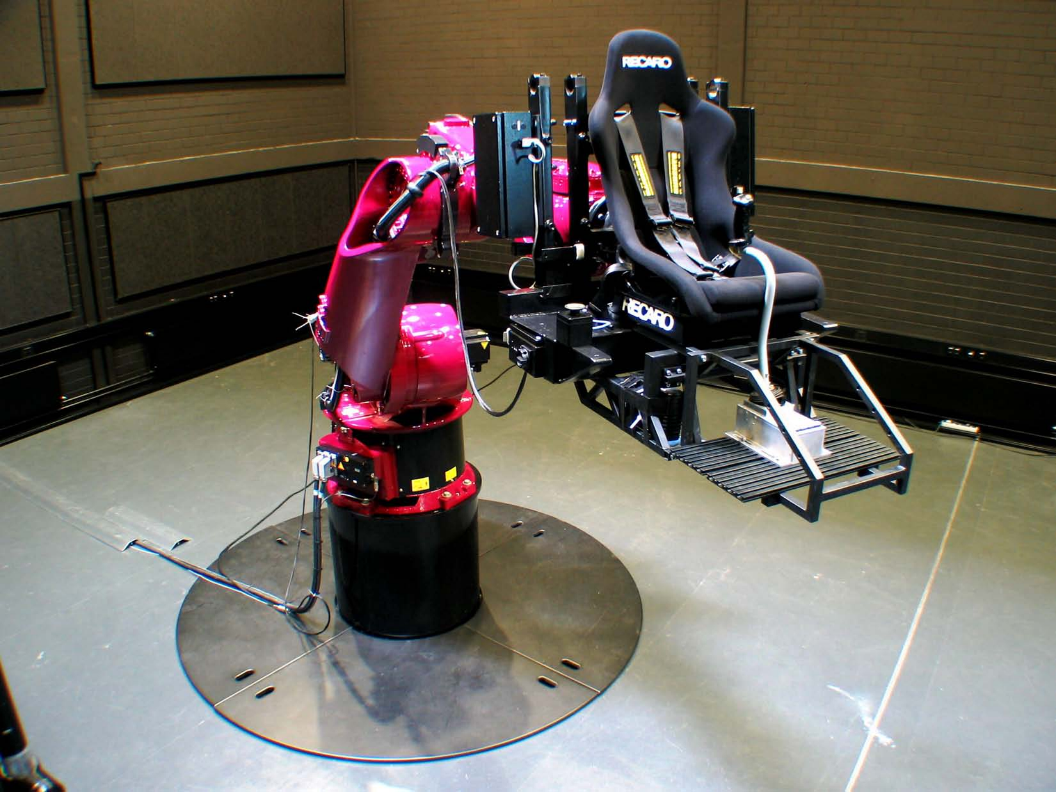
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