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ORIGINAL ARTICLE

Designing presence for real locomotion in immersive virtual environments: an affordance-based experiential approach

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Abstract This paper describes a framework for designing systems for real locomotion in virtual environments (VEs) in order to achieve an intense sense of presence. The main outcome of the present research is a list of design features that the virtual reality technology should have in order to achieve such a goal. To identify these features, an approach based on the combination of two design strategies was followed. The first was based on the theory of affordances and was utilized to design a generic VE in which the affordances of the corresponding real environment could be evoked. The second was the experiential design applied to VEs and was utilized to create an experience of locomotion corresponding to that achievable in a real environment. These design strategies were chosen because of their potential to enhance the sense of presence. The proposed list of features can be utilized as an instrument that allows VE designers to evaluate the maturity of their systems and to pinpoint directions for future developments. A survey analysis was performed using the proposed framework, which involved three case studies to determine how many features of the proposed framework were present and their status. The result of such analysis represented a measure of the completeness of the systems design, of the affordances provided to the user, and a prediction of the sense of presence.

Keywords Affordance · Experiential design · Locomotion interfaces · Virtual environments · Presence

1 Introduction

In the last decades, much research has been done to design technology to allow users to navigate virtual environments (VEs) by means of real locomotion (i.e., the user's act of physically moving from place to place), in particular real walking (Steinicke et al. 2013). Various studies have provided evidence that real walking is the optimal interaction technique for navigation of immersive VEs since it produces a higher sense of immersion, increases naturalness, and improves task performance compared to other solutions (Slater et al. 1995; Usoh et al. 1999; Zanbaka et al. 2005; Ruddle and Lessels 2009; Peck et al. 2012).

Several technological solutions have been developed with the goal of providing users navigating the VE with sensory stimulations capable of producing a sensory flow that could lead to the same percept experienced during walking in the corresponding real environment [for recent review, see (Steinicke et al. 2013)]. More generally, virtual reality (VR) technology aims to allow users to experience a reality different from the one they physically inhabit. This subjective experience of "being there" inside the virtual world is referred to as "presence" (Heeter 1992). Slater and colleagues considered presence as "the propensity of people to respond to virtually generated sensory data as if they were real" (Slater et al. 2009). They suggested that a user, experiencing an intense sense of presence in a virtual environment, would exhibit physiological and behavioral responses comparable to those produced while experiencing a similar real-world environment. In a subsequent work, Slater argued that users tend to respond realistically to situations and events portrayed within an immersive VE when both "place illusion" and "plausibility illusion" occur (Slater 2009). The former is the illusion of being in a place despite the sure knowledge of not being there. The

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latter is the illusion that what is apparently happening is really happening despite the sure knowledge that is not.

To achieve such illusions during the navigation of VEs by means of real locomotion, system design concepts are needed. Although several recommendations have been proposed to implement systems for real locomotion in VEs (Steinicke et al. 2013), limited attention has been devoted to guidelines specifically defined to achieve an intense sense of presence. The objective of this paper is to address these guidelines. For this purpose, a framework is proposed, which encompasses both an ecological design based on Gibson's theory of affordances (Gibson 1979), and a holistic design based on experiential design (Pine and Gilmore 2011; Chertoff et al. 2008, 2010).

On the one hand, for a VE to be meaningful in the ecological sense, users must be provided with coherent relations between perception and action. Nevertheless, the ecological validity of a VE is largely contingent on designers' accurate understanding of the nature of its affordances. Interestingly, research has demonstrated that affordances of a real environment are perceived in body-scaled terms (e.g., height, width, leg length, running speed), thus indicating that individuals perceive the properties of the environment in relation to themselves (Warren 1984; Mark 1987; Warren and Whang 1987; Oudejans et al. 1996; Fajen 2013). On the other hand, designing the experience of the user requires the understanding of all the factors involved in the user's interaction with the VE, not only those related to the sensory stimulation, but also those related, for example, to cognitive and affective aspects. These considerations motivate the research reported in the present study. By combining the ecological approach with the experiential one, this work attempts to answer both the need to integrate a comprehensive theory of locomotion perception into VE design and the call of Chertoff et al. to: "begin to explore the holistic experience of participating in mediated environments" (Chertoff et al. 2008).

The main outcome of the present research is a list of design features that VR technology should have for the purpose of achieving strong place and plausibility illusions during real locomotion in a generic VE. Such a list can be utilized as an instrument that allows VE designers to evaluate what aspects of their technology need to be further developed, such that future iterations can be improved.

2 Affordances in VR

The ecological approach to perception and action has been considered as promising for designing VEs capable of providing a realistic experience (Flach and Holden 1998; Zahorik and Jenison 1998; Gross et al. 2005; Schubert 2009). However, so far only a handful of studies have investigated the role of affordances in VR contexts and in particular in locomotion in VE (Fajen 2013). With the aim of providing guidelines to VE designers for generating more ecologically valid designs, Gross et al. presented a conceptual model for evoking affordances in VEs via sensory substitution schemes (Gross et al. 2005). In addition, they argued that for the realization of affordances in VE, sufficiency in sensory stimulation, perception of body stature, and action possibilities are required.

Lepecq et al. asserted that the degree of place illusion in a VE can be evaluated by its actual affordances for action (Lepecq et al. 2009). To test such a hypothesis, they performed an experiment in which subjects were asked to walk straight through a virtual aperture of variable widths with a self-selected speed. Shoulders positions and rotations during walking through the aperture were measured based on the use of reflective markers. The analysis of the collected data showed that subjects exhibited in the VE the basic behavioral properties already observed in corresponding real environments for the same task of walking through a real aperture (Warren and Whang 1987). Their study, therefore, suggested that every afforded action could be a potential tool for sensorimotor assessment of place illusion in a VE. Along the same line, Regia-Corte et al. (2013) studied the perception of affordances in VEs considering the case of standing on a slanted surface with different textures (woody or icy). Results showed that subjects were capable of exploiting virtual information about surface friction in order to judge whether a slanted surface supported an upright stance. More importantly, subjects' evaluations were comparable to those reported in previous studies conducted in real environments (Fitzpatrick et al. 1994). It is important to consider that affordances in VEs have been proved to be profoundly affected by the properties of the utilized interfaces (Grechkin et al. 2014).

3 Experiential design

Experiential design (ED) is an approach used in marketing to create strategically compelling and memorable experiences (Pine and Gilmore 2011). It consists of the process of creating a desired consumers' experience. Such a process leverages the consumers' previous experience stored in memory in order to create positive associations between it and the product. Five dimensions of the experience are considered in a holistic framework: sensory (i.e., sensorial stimulations), cognitive (i.e., tasks), affective (i.e., emotional connections), active (i.e., sense of agency), and relational (i.e., social aspects). By designing such a holistic experience, the consumers can create meaningful emotional and social connections to a product: They can recall episodic memories about the designed experience, and if they enjoyed the artifacts of that experience, will build positive associations with the product. Therefore, a fundamental tenet of ED is considering how previous experiences can be integrated into new experiences. When consumers are subjected to new experiences, they use experiences stored in memory to make new decisions and process new information.

In the context of VR, ED has been proposed as a method to enhance presence in VEs (Chertoff et al. 2008). Table 1 (middle column) reports the five dimensions of ED applied toward VEs, as illustrated in Chertoff et al. (2010). By designing a holistic experience in which all these dimensions are integrated, a user can fill the information not provided by the VE by recalling his previous experience. According to Slater, this process has the potential to increase the user's sense of presence (Slater 2002). As a consequence, better performances can be achieved (Barfield et al. 1995). The enhancement of the sense of presence theorized in Chertoff et al. (2008) was experimentally confirmed in the study reported in Chertoff et al. (2010). Participants were asked to interact with a commercial video game configured in order to utilize the dimensions of ED in different ways and to complete presence questionnaires. Results showed a significant increase in presence for the game configurations that made better use of the five dimensions in the design process. The same study presented and validated the virtual experience test, a questionnaire based upon the five dimensions of ED. The validation proved its effective usage to measure holistic VE experiences and showed that non-sensory components of experience are also related to presence. Inspired by the description of the dimensions reported in Chertoff et al. (2010), the right column in Table 1 reports the author's application of the ED dimensions toward locomotion in VEs.

4 Affordance-based experiential design

Taken together, the studies reported in Gross et al. (2005), Lepecq et al. (2009), and Regia-Corte et al. (2013) indicated that affordances can be evoked in VEs and that their perception in the synthetic world can be influenced by both environmental and body properties. Starting from those findings, the concept of affordances was applied to the design of locomotion interfaces for immersive VEs. The first design objective was to evoke in a VE the affordances of the corresponding real environment.

Table 1 Dimensions of experiential design

ED dimension	Description (for VEs)	Description (for locomotion in VEs)
Sensory	Includes sensory input (visual, aural, haptic, etc.) as well as perception of those stimuli. Represented through sensory hardware and software that creates the sensations	Includes sensory input, with a particular focus on plantar tactile feedback and proprioception, as well as perception of those stimuli, with a particular focus on self-motion perception. Represented through locomotion interfaces and software tools capable of simulating multisensory stimuli resulting from locomotion and foot–floors interactions
Cognitive	Mental engagement with an experience, such as anticipating outcomes and solving mysteries. Can be interpreted as task engagement	Mental engagement with the locomotion experience, such as anticipating changes in landscape and soundscape due to the navigation in the virtual environment. Can be interpreted as engagement in the locomotion task
Affective	Refers to the user's emotional state. Related to the degree to which a person's emotions in the simulated environment would accurately mimic his emotional state in a similar real-world situation	Refers to the user's emotional state during the locomotion in the virtual environment. Related to the degree to which a person's emotions experienced while navigating in the simulated environment would accurately mimic his/her emotional state in a similar real-world situation
Active	Relates to the degree of personal connection a person feels to an experience. Associated with the degree of empathy, identification, and personal relation a person feels to the virtual environment's avatars, surroundings, and scenario	Relates to the degree of personal connection a person feels to the locomotion experience. Associated with the degree of empathy, identification, and personal relation a person feels to the virtual environment's avatars, landscape, and soundscape
Relational	Comprised of the social aspects of an experience. Operationalized as co-experience; creating and reinforcing meaning through collaborative experiences	Comprised of the social aspects of the locomotion experience. Operationalized as co-experience; creating and reinforcing meaning through collaborative experiences, such as walking together with the avatar of a human being

In the middle column are presented those applied toward virtual environments reported from Chertoff et al. (2010); in the right column those applied toward locomotion in virtual environments [inspired by (Chertoff et al. 2010)]

The underlying methodology used in this work is that of affordance-based design (ABD) developed by Maier and Fadel (2009a, b). Such an approach describes and explains the relationships between users and designed artifacts and allows designers to analyze concepts with respect to desired and undesired affordances in early phases of the design process. In more detail, the proposed design aimed to avoid hidden affordances (i.e., actions that are possible but are not perceived as such by actors) and false affordances (i.e., actions that are not possible but are perceived by actors as possible), as defined in Gaver (1991): Particular attention was indeed devoted to the identification of the ideal set of user's valid actions that have the potential to occur in the VE. The term "valid actions" is here intended according to the definition given by Slater as "the actions that a participant can take that can result in changes in perception or changes to the environment" (Slater 2009). In addition, the design took into account the guidelines proposed in McGrenere and Ho (2000), Hartson (2003), and Gross et al. (2005).

The reason to adopt the ABD is that it should allow users to readily perceive which are the possible actions during the real locomotion in a VE, as well as to exploit the same skills acquired via real-world actions associated with locomotion (Flach and Holden 1998; Gross et al. 2005). A VE in which all the affordances of the corresponding real environment are evoked would produce a high degree of place illusion (Lepecq et al. 2009). In addition, if the involved VR technology is capable of sufficiently stimulating the senses (Gross et al. 2005), then strong plausibility illusions would occur.

On the other hand, ED provides a framework that can be applied to the design of VEs. Such a framework can complement ABD. As suggested by the results reported in Chertoff et al. (2010), the design of a VE should be conceived considering a user's holistic experience. Therefore, that holistic approach was applied to the design of locomotion interfaces for immersive VEs. The second design objective was thus to create an experience of locomotion corresponding to that achievable in a real environment.

To achieve the two objectives described above, a methodology to guide the design process was defined. It consisted of the following steps:

1. Identification of the affordances associated with locomotion in real environments that should be realized by the VR technology;
2. Identification of general objectives defining the user's experience of locomotion in VEs;
3. Identification of features that VR technology should have in order to realize both the affordances determined in the first step and the content of the experience described in the second step;
4. Identification of the means to realize the features defined in the third step.

The whole design process was conceived to be applied to a user's locomotion experience in a VE as general as possible. Therefore, specific VR contexts (e.g., rehabilitation) are not the target. Nevertheless, by keeping general the scenario, such specific contexts are included. In the reminder of this section, the first three steps are addressed. The fourth step will be addressed in future research.

4.1 Affordance identification

Two elements were considered to identify affordances associated with locomotion in real environments: the environment and the individual's body. As far as the environment-related affordances are concerned, they were identified in the following categories:

Foot–floor interactions: The floor affords different types of interactions by means of the actor's feet. It affords an actor to produce steps, slip, brush the feet on it, interact with heel and toes as well as with different dynamics (e.g., strong or soft impacts), and, depending on the compliance of the surface material, sink.

Navigability: The environment affords an actor to perform various navigation possibilities, such as to walk, jump, run, sprint, or limp; to slip, stumble, or fall down; to start and stop the locomotion at any time; to change the locomotion direction; to perform endless locomotion; to perform locomotion at different speeds; to climb or climb down.

Sensing: As a result of the individual's locomotion, the environment affords an immediate and synchronized multimodal feedback as well as changes in landscape, soundscape, weather conditions (e.g., temperature, humidity), and odors. It also affords movements of objects/organisms along tridimensional trajectories.

As far as the body-related affordances are concerned, they were identified in the following categories:

Body ownership: The body affords to be perceived through visual cues (e.g., seeing the feet), auditory cues (e.g., footstep sounds or the sounds resulting from the rubbing of the clothes), as well as vestibular cues (e.g., perceiving the position of the feet).

Body wearability: The body affords to wear clothes and shoes.

Body physiology: The body affords to see and hear from a certain height from the ground. This depends on the stature and body posture (e.g., upright, stooped) to move toward one direction while gazing at another; to move with a specific pace that depends on the individual's anthropomorphic features (e.g., gender, weight, leg length), locomotion style, and eventually presence of impairments.

It is interesting to notice the relations between the identified categories of affordances. For example, the affordances in the foot–floor interaction are related to the navigability affordances offered by the geometry of the environment. For instance, an environment affording walking actions affords steps. Similarly, the affordances of the body wearability are related to all the other affordances categories. For instance, the fact that the body affords to wear a specific type of shoe is linked to the possibility of perceiving the body as well as the environment through specific footstep sounds, which in turn are also related to the types of interactions afforded by the floor. Those sounds are perceived according to the affordances given by the users anthropomorphic features. Moreover, that particular type of shoes can affect the speed of navigation.

4.2 Designing the user's experience

The design of the user's experience of real locomotion in a VE produced the following objectives according to the five dimensions of ED:

Sensory: The user is provided with sufficient as well as temporally, spatially, and semantically congruent multisensory stimuli representing his/her own body, the environment, and the interaction of his/her body with the environment.

Cognitive: The user is free to move and perceives his/her body during locomotion. He/she perceives that the environment reacts to his/her action in a way consistent with real-world interactions, as well as that the environment produces events that are in agreement with expectations based on his/her prior experience.

Affective: During locomotion, the user can express through his/her body movements, his/her emotions. The environment is effective in inducing an emotional state (including the neutral state where no particular emotion is induced).

Active: During locomotion, the user can perceive his/her own anthropomorphic features (e.g., stature, gender, weight), footwear, clothes, and body posture.

Relational: The user can interact with other agents (animals, humans, other users) if present in the environment and perceives that his/her interaction with those agents is consistent with real-world interactions.

At the basis of the identification of these objectives, there were several results from both presence and perception research. Specifically, from the former, results concerning the causes for which presence occurs were taken into account (Lee 2004; Harvey and Sanchez-Vives 2005). From the latter, results concerning multisensory perception, especially those related to locomotion in real and virtual environments, were considered (Steinicke et al. 2013).

As far as the sensory dimension is concerned, on the one hand, the listed objectives were motivated by results indicating the importance of providing stimuli from different sensory modalities on the sense of presence in VEs (Dinh et al. 1999; Biocca et al. 2002; Larsson et al. 2010; Fröhlich and Wachsmuth 2013). On the other hand, those objectives were derived from the fact that temporal, spatial, and semantic coherences are important factors for multisensory integration (Spence 2007; Calvert et al. 2004): Incoherence between stimuli provided to different sensory modalities affects negatively their binding into a unitary percept and this results in breaks in presence (Harvey and Sanchez-Vives 2005). In addition, the objective of rendering the user's body was supported by the importance of the feeling of body ownership for the sense of presence, as highlighted in Slater (2009) and Spanlang et al. (2014).

The objectives resulting from the cognitive dimension were also supported by results motivating the objectives of the sensory dimension. Particular attention was devoted to the semantic congruence, especially for the case of foot–floor interactions (Giordano et al. 2012; Turchet and Serafin 2014). In addition, cross-modal correspondences between stimulus features in different sensory modalities were taken into account as a factor relevant for multisensory integration [for a review, see (Spence 2011)] and, therefore, related to presence (Harvey and Sanchez-Vives 2005).

Regarding the affective dimension, firstly the listed objectives were based on the results indicating the relationship between presence and emotions (Riva et al. 2007), and between presence and sense of arousal (Heeter 1995). Secondly, they were motivated by results reported in Giordano and Bresin (2006), which investigated the auditory recognition of walks performed with different emotional intentions. Such findings showed that strong similarities were present between walking and musical expression of emotions with respect to acoustical variables such as temporal evolution and sound level. Thirdly, they were supported by findings that showed how properties of the environment are capable of altering a person's emotional state [for example, odors can produce changes in the mood state (Van Toller and Dodd 1988, 1992)].

The objectives related to the active dimension, on the one hand, were supported by results showing that footstep sounds convey information about the gender (Li et al. 1991), the footwear sole hardness (Giordano and Bresin 2006), the identity of a person (Mäkelä et al. 2003), and even his/her body posture (e.g., upright, stooped) (Pastore et al. 2008). On the other hand, they were supported by results indicating that affordances of an environment are perceived in body-scaled terms (Warren 1984; Mark 1987; Warren and Whang 1987; Oudejans et al. 1996). Finally, the objectives resulting from the relational dimension were based on results that showed that presence is higher in social contexts (Heeter 1992; Ravaja et al. 2006).

4.3 Design features identification

The affordances identified by the ABD as well as the objectives resulting from ED were converted into a list of features for the VR technology involved in the simulation of the real locomotion in VEs. They are illustrated in Tables 2, 3, and 4. The features were classified in three categories: "sensing features" (SF), i.e., those capable of detecting in real time various aspects of the user's locomotion; "navigation features" (NF), i.e., those related to the exploration of the VE during locomotion; "display features" (DF), i.e., those involved in the interactive display of the multimodal feedback resulting from the user's actions. The sensing features were further subdivided in "body tracking" (BT), i.e., the features related to the tracking of the relevant parts of the body, "foot–floor contact sensing" (FF), i.e., the features related to the sensing of various aspects of the interaction of the foot with the floor, and "multiple users tracking" (MUT), i.e., the features related to the tracking of multiple users navigating in the VE. The navigation features were further subdivided into "general navigation features" (G), i.e., those related to general aspects of the navigation in VEs, "locomotion" (L), i.e., those related to various aspects of locomotion, "exploration" (E), i.e., those related to the exploration of the VE. The display features were further subdivided into "general display features" (G), i.e., those related to general aspects of the feedback display, "perceptually convincing multimodal rendering" (MR), i.e., those related to various aspects of the multimodal stimulation, "multiple users rendering" (MUR), i.e., the features related to the rendering of multiple users navigating in the VE.

In addition to this, many of the identified features were heavily based on results emerging from the guidelines for the design of locomotion interfaces proposed in Steinicke et al. (2013), the guidelines for body tracking and virtual body rendering proposed in Spanlang et al. (2014) in order to produce body ownership illusions, as well as the conditions for presence proposed in Slater et al. (2009).

5 Practical application of the list of features

Although the proposed design process was heavily based on existing affordance, experiential design, and presence theory, it still requires validation to ensure that the features illustrated in Sect. 4.3 are effective in pursuing the goal of

Table 2 The identified sensing features

Body tracking	
	The system is capable of tracking with sufficient accuracy the parts of the body that can be seen, heard, or felt by the user during locomotion:
SF_BT_1.1	Separate tracking of the left and right foot
SF_BT_1.2	Separate tracking of the heel and toe in each foot
SF_BT_1.3	Separate tracking of the legs
SF_BT_1.4	Tracking of the torso
SF_BT_1.5	Separate tracking of the hands (and their fingers)
SF_BT_1.6	Separate tracking of the arms
SF_BT_2	The system is capable of tracking with sufficient accuracy the head
SF_BT_3	The system is capable of tracking with sufficient accuracy the eyes
Foot-floor contact sensing	
SF_FF_1	The system is capable of detecting different types of foot–floor interactions (e.g., walking steps, running steps, jumps, the brushing of the feet on the floor)
SF_FF_2	The system is capable of distinguishing different types of foot–floor interactions (e.g., walking steps vs the brushing of the feet on the floor)
SF_FF_3	The system is capable of detecting with sufficient accuracy different dynamics of the foot–floor interactions (e.g., different levels of impact forces)
SF_FF_4	The system is capable of detecting with sufficient accuracy different speeds of locomotion
Multiple users tracking	
SF_MUT_1	The system is capable of separately tracking with sufficient accuracy the locomotion of multiple users
SF_MUT_2	The system is capable of separately tracking with sufficient accuracy the interactions between each user (e.g., gestures, vocal communication)

SF sensing feature, *BT* body tracking, *FF* foot–floor contact sensing, *MUT* multiple users tracking

Table 3 The identified navigation features

General navigation features	
	The system provides users with total freedom of movement (i.e., the presence of the system does not constitute any obstacle to the users' navigation and does not disturb VR immersiveness):
NF_G_1.1	Wireless connectivity
NF_G_1.2	Discontinuous contact between the foot and the virtual floor during the swing phase
NF_G_1.3	Easy wearability
NF_G_1.4	Lightness and comfortability
NF_G_2	The system provides users with safe interactions (i.e., the system prevents the user from slipping, stumbling, or falling down)
Locomotion	
	The system allows users to perform different types of locomotions:
NF_L_1.1	Walking
NF_L_1.2	Running
NF_L_1.3	Jumping
NF_L_1.4	Sprinting
NF_L_2	The system allows users to start and stop the locomotion at any time
NF_L_3	The system allows users to vary their locomotion speed
	The system allows users to vary their locomotion direction:
NF_L_4.1	Toward left and right
NF_L_4.2	Toward front and back
NF_L_4.3	Toward up and down
NF_L_5	The system allows users to perform an endless locomotion
Exploration	
NF_E_1	The system allows users to move in one direction while gazing at another
NF_E_2	The system allows users to change their body posture (e.g., upright, stooped)
NF_E_3	The system allows users to brush the foot on the floor

NF navigation feature, *G* general, *L* locomotion, *E* exploration

achieving an intense sense of presence. To investigate the validity of such features, a proper study would consist of evaluating the sense of presence achieved by participants interacting with a system embedding all of them [for example, for this purpose the questionnaire proposed in Chertoff et al. (2010) could be used]. However, to date such system is not available since the technology required to implement all those features has not been developed yet.

Nevertheless, the identified features can be utilized as an instrument to evaluate the maturity of a system such that the greater the number of the developed features, the greater the predicted sense of presence. More importantly, by analyzing a system according to such list of features, it is possible to identify which aspects of the developed technology need further work. Therefore, hereinafter an application of the identified features is described with the aim of showing how they can be practically used. Three systems among the most advanced ones currently implemented were considered as case studies, along with their possible extensions achievable by integrating thoroughly additional technological solutions available today in other systems. They are briefly summarized below.

Shoe-based architecture (SBA). This system consists of a HMD, a pair of wired shoes enhanced with pressure sensors and vibrotactile actuators, a multichannel surround sound system with algorithms for sound sources tridimensional spatialization, and an optical motion capture system, which tracks markers placed on user's head and feet to control the visual feedback and to inform the user about the boundaries of the tracked space (Nordahl et al. 2012; Turchet et al. 2012). The shoes' pressure sensors and actuators are placed in correspondence of heel and toe. They are used to drive a physically based audio-tactile synthesis engine that simulates the act of walking on different surface materials (Turchet et al. 2010). However, no foot–floor dynamics are rendered and the HMD's box produces an audible noise. Moreover, the navigation is limited by the wires of both HMD and shoes. Footstep sounds and soundscapes are displayed along tridimensional trajectories. The feet of the avatar of the user is visually displayed.

CyberWalk platform (CWP). This system consists of an omnidirectional treadmill which allows users to walk in a way very close to that of real world (Frissen et al. 2013;

Table 4 The identified display features

General display features	
DF_G_1	The system provides users with low latency feedbacks (i.e., not perceivable delay between users' actions and corresponding feedback)
	The system provides users with sufficient multisensory stimulation in terms of quality of the display hardware and display content
DF_G_2.1	Audio (e.g., frequency response; 3D reproduction of sound sources moving in the environment; silent hardware, i.e., the involved technology does not produce sounds that can interfere with the auditory display)
DF_G_2.2	Video (e.g., stereoscopic vision, graphics frame rate, field of view, resolution in terms of brightness, contrast, space, or color)
DF_G_2.3	Haptic (e.g., range of forces, range of vibrations, number of degrees of freedom, range of temperatures and humidity)
DF_G_2.4	Smell, wind, humidity, and thermal properties of the environment
	The system provides users with temporally coincident multimodal stimulation:
DF_G_3.1	Related only to the body display (e.g., the user moves an arm and at the same time sees the avatar's arm moving)
DF_G_3.2	Related only to the environment display (e.g., the user sees a bee moving and at the same time listens to its sounds)
DF_G_3.3	Related to the display of the interaction of the body with the environment (e.g., synchronization between footstep sounds and footfalls)
	The system provides users with spatially coincident multimodal stimulation:
DF_G_4.1	Related only to the body display (e.g., the user moves an arm in a location and sees the avatar's arm moving in that location)
DF_G_4.2	Related only to the environment display (e.g., the user sees a bee moving and perceives its sounds as coming from it)
DF_G_4.3	Related to the display of the interaction of the body with the environment (e.g., during a step, the user feels the sensations arisen to the feet and perceives the resulting sound as coming from the feet)
	The system provides users with semantically congruent multimodal stimulation
DF_G_5.1	Related only to the body display (e.g., the user moves an arm in a location and perceives the avatar's arm as if it was his/her own)
DF_G_5.2	Related only to the environment display (e.g., the user sees a bee moving and perceives its sounds as appropriate for a bee)
DF_G_5.3	Related to the display of the interaction of the body with the environment (e.g., the user perceives that the plantar vibrotactile stimulation is appropriate for the displayed footstep sound simulation)
Perceptually compelling multimodal rendering	
	The system is capable of rendering at multimodal level, i.e., at aural, haptic (i.e., touch, kinesthesia, temperature), visual, vestibular, and/or olfactory level:
DF_MR_1	Cues corresponding to the user's displacement (e.g., changes in the landscape according to the user's position in the environment, as well as head and eyes position; changes in the soundscape according to the user's position in the environment, as well as head position; changes in the odors according to the user's position in the environment; changes in the weather conditions)
DF_MR_2	Various types of foot–floor interactions (e.g., normal steps, running steps, jumps, brushing)
DF_MR_3	Various surface slopes and profiles (e.g., bumps, holes, flat)
DF_MR_4	Local unevenness of the terrain (e.g., potholes or bulges)
DF_MR_5	A large palette of surface materials, especially their properties relevant at perceptual level, e.g., typology (solid, aggregate, liquid, hybrid materials), compliance, viscosity, slipperiness
DF_MR_6	Various types of footwear and clothes (or the user should be dressed appropriately for the rendered environment)
DF_MR_7	The anthropomorphic features of the user (e.g., stature, gender, weight, foot size, leg length, etc.)
DF_MR_8	The body posture of the user (e.g., upright, stooped)
DF_MR_9	The parts of the body that can be seen, heard, or felt by the user during locomotion (e.g., feet, legs, arms)
DF_MR_10	Separately the gaze direction from the locomotion direction
Multiple users rendering	
DF_MUR_1	The system is capable of rendering separately the locomotion of multiple users and their interactions
DF_MUR_2	The system is capable of rendering separately the interactions between each user

DF display feature, *G* general, *MR* multimodal rendering, *MUR* multiple users rendering

Souman et al. 2011). Users are allowed to start and stop walking, vary their walking speed and direction, and walk endlessly in any direction. Running is possible for experienced users. However, slopes and local unevenness of the ground are not rendered. An optical tracking system is capable of full body tracking. The tracked position and orientation of the user's head is used both for treadmill control and for visualization (provided through a HMD). Auditory feedback is also provided, and some demos have used the visualization of the user's own avatar. Users are required to wear a safety harness connected to the ceiling, to prevent them from falling.

TreadPort Active Wind Tunnel (TPAWT). This system consists of the integration of the TreadPort locomotion interface (Hollerbach et al. 2000) with a wind tunnel for atmospheric display (Kulkarni et al. 2009, 2012). The TreadPort is composed by a CAVE-like visual interface, as well as a harness and a treadmill that provide accurate locomotion forces as a user walks through a virtual environment. The atmospheric display is capable of controlling wind speed and angle acting on a user in the environment. It can provide olfactory and radiant heat display, by injecting scent particles and warm air into the wind tunnel.

Extended SBA (XSBA). SBA can be integrated with a portable eyes tracking device and with visual (Bruder et al. 2012) or audio-visual (Peck et al. 2012) redirection techniques that can complement the system for redirection based on ecological audio-tactile feedback presented in Turchet et al. (2012). The visual feedback could adopt the visual interaction techniques proposed by Marchal et al. (2010) to generate illusions of walking up or down on uneven surfaces. The tracking system can be extended to achieve a full body detection. Recently, the shoes have been improved both at hardware and at software level by Zanotto et al. (2014): They are equipped with better embedded actuators; a greater number of actuators is involved; inertial sensors have been added; the auditory feedback comes directly from the feet thanks to small loudspeakers placed on the side of each shoe; the system is fully portable (no wires link the shoes to a computer running the synthesis engine); different types of foot–floor interaction (e.g., walking step, jumping step, scuffs) as well as the foot–floor dynamics are rendered thanks to the interactive sonification (Hermann et al. 2011) of the data coming from the inertial sensors (Turchet 2014). In addition, it is possible to integrate the set of audio-tactile tiles developed by Visell et al. (2009) in order to create stronger tactile sensations about self-motion. Furthermore, SBA can be extended by adding systems for the display of scent (Yanagida et al. 2004), wind, and warmth (Hülsmann et al. 2014).

Extended CWP (XCWP). CWP can be integrated with a portable eyes tracking device, headphones, or a surround sound system with algorithms for sound sources tridimensional spatialization and with the audio-tactile shoes proposed by Zanotto et al. (2014). Local unevenness of virtual terrains could be simulated thanks to solutions similar to the series of linear actuators underneath the belt involved in GSS. The visual feedback could adopt the visual interaction techniques proposed by Marchal et al. (2010) to generate illusions of walking up or down on uneven surfaces. In addition, CWP can be extended by adding systems for the display of scent (Yanagida et al. 2004), wind, and warmth (Hülsmann et al. 2014).

Extended TPAWT (XTPAWT). TPAWT can be integrated with headphones or a surround sound system with algorithms for sound sources tridimensional spatialization and with the audio-tactile shoes proposed by Zanotto et al. (2014). In addition, it can be extended by adding the warmth display presented by Hülsmann et al. (2014).

These four systems were evaluated by assigning to each feature one of the following four scores reflecting the progress of that feature: fully accomplished (F), partially accomplished (P), partially accomplished but improved compared to a previous version (P_+), and absent (A). Such evaluation was mostly based on the information available in the literature, as well as other resources available in the Internet and the author's personal experience in developing the SBA system. In absence of enough information for a feature of a system, the A score was assigned. Three tables were created for the three identified categories of features: Table 5 illustrates the scores for the sensing features, Table 6 for the navigation features, and Table 7 for the display features. By comparing the evaluations of the SBA, CWP, and TPAWT systems with their extended version, it is possible to notice how for the latter some features were evaluated F in place of P and A, P in place of A, and P_+ in place of P. As a consequence, XSBA, XCWP, and XTPAWT systems would lead to higher states of presence compared to SBA, CWP, and TPAWT, respectively. Moreover, from the three tables, it is possible to notice which features in each category are missing and which are not fully accomplished. These represent directions for future improvements in the system in order to achieve the goal of producing an intense sense of presence. For example, in addition to the proposed extensions, future developments of the three systems should focus on improving the technology toward solutions that allow wireless connectivity. Nevertheless, these considerations are not the main goal of the present work.

6 Discussion and conclusions

The framework described in this paper was motivated by a particular problem: how to design systems for real locomotion in a generic VE, capable of producing strong place and plausibility illusions. The first step taken toward the solution of this problem was to determine which features a system should have. To identify such features, an approach based on the combination of two design strategies was followed. The first was an approach based on the theory of affordances and was utilized to design a generic VE in which all the affordances of the corresponding real environment could be evoked. The second was ED applied to VEs and was utilized to create an experience of locomotion

Table 5 Table of scores for sensing features

System	SF_BT_1.1	SF_BT_1.2	SF_BT_1.3	SF_BT_1.4	SF_BT_1.5	SF_BT_1.6	SF_BT_2	SF_BT_3	SF_FF_1	SF_FF_2	SF_FF_3	SF_FF_4	SF_MUT_1	SF_MUT_2
SBA	F	F	A	A	A	A	F	A	A	A	A	A	A	A
XSBA	F	F	**F**	**F**	**F**	**F**	F	**F**	**F**	**F**	**F**	A	A	A
CWP	F	F	F	F	F	F	F	A	A	A	A	F	A	A
XCWP	F	F	F	F	F	F	F	**F**	**F**	**F**	**F**	F	A	A
TPAWT	A	A	A	P	A	A	A	A	A	A	A	F	A	A
XTPAWT	**F**	**F**	A	P	A	A	A	A	**F**	**F**	**F**	F	A	A

The features improved in the systems extended version are provided in bold

SF sensing feature, *BT* body tracking, *FF* foot–floor contact sensing, *MUT* multiple users tracking, *SBA* Shoe-based architecture, *XSBA* extended shoe-based architecture, *CWP* CyberWalk platform, *XCWP* extended CyberWalk platform, *TPAWT* TreadPort Active Wind Tunnel, *XTPAWT* extended TreadPort Active Wind Tunnel

corresponding to that achievable in a real environment. These design strategies were chosen because of their potential to enhance the sense of presence. Both theoretical and empirical evidence was cited in support of the proposed framework. An analysis of three case study systems was performed by means of the identified features, providing some initial support for the framework. It was shown that the list of features can be used in a practical way by VE designers as series of guidelines to evaluate the maturity of their systems and to pinpoint directions for future developments.

The present research highlights the importance of considering two aspects when designing systems for real locomotion in VEs, with the goal of producing an intense sense of presence. The first is the use of a holistic approach that encompasses on the one hand both environment and body affordances and on the other hand all dimensions of the experience, not just the sensory one, which is what usually is the case. It is argued that when creating VEs in order to accurately simulate real environments, it is necessary not only to simulate all the perceptually important real-world sensorial stimuli, but also to allow the largest set of valid actions possible, as well as to provide a sensorial content that takes into account cognitive, affective, active, and relational aspects of the experience.

The second aspect is the rendering of the virtual body in a way consistent with the user's body in order to produce a strong feeling of body ownership (Spanlang et al. 2014). Gross et al. (2005) posed the attention on the perception of body stature in the VE. Here, it is argued that it is not only the body stature that needs to be perceptually rendered, but also all of the user's other anthropomorphic features (e.g., gender, weight, foot size, leg length, etc.) with particular regard to those that can be seen, heard, or felt by the user during locomotion. For example, previous research has demonstrated that it is possible to recognize the walker's gender (Li et al. 1991), identity (Mäkelä et al. 2003), emotions (Giordano and Bresin 2006), and body posture (Pastore et al. 2008) based on auditory information alone contained in footstep sounds, suggesting therefore that an appropriate auditory rendering of the user's anthropomorphic features can play an important role in the body awareness during the simulated locomotion. In addition, the present study suggests the importance of simulating the sensation of wearing specific shoes and clothes. Future research could assess the role played by different types of clothes on the sense of presence, especially when several properties of the climate of the environment (e.g., temperature, humidity) are also rendered. The impression of wearing clothes and footwear coherent with the VE (e.g., a ski suit in a snowy environment) should then lead to an increase in presence.

It is worthwhile to notice that the proposed list of features aim at defining what needs to be done, rather than

Table 6 Table of scores for navigation features

System	NF_G_1.1	NF_G_1.2	NF_G_1.3	NF_G_1.4	NF_G_2	NF_L_1.1	NF_L_1.2	NF_L_1.3	NF_L_1.4
SBA	A	F	A	A	A	F	A	A	A
XSBA	A	F	A	**P**	A	F	A	A	A
CWP	A	F	A	A	F	F	P	A	A
XCWP	A	F	A	A	F	F	P	A	A
TPAWT	A	F	A	A	F	F	A	A	A
XTPAWT	A	F	A	A	F	F	A	A	A

System	NF_L_2	NF_L_3	NF_L_4.1	NF_L_4.2	NF_L_4.3	NF_L_5	NF_E_1	NF_E_2	NF_E_3
SBA	F	P	F	P	A	A	F	P	F
XSBA	F	P	F	P	A	**P**	F	P	F
CWP	F	F	F	P	A	F	F	P	F
XCWP	F	F	F	P	A	F	F	P	F
TPAWT	A	A	A	P	A	F	F	A	F
XTPAWT	A	A	A	P	A	F	F	A	F

The features improved in the systems extended version are provided in bold. *NF* navigation feature, *G* general, *L* locomotion, *E* exploration, *SBA* shoe-based architecture, *XSBA* extended shoe-based architecture, *CWP* CyberWalk platform, *XCWP* extended CyberWalk platform, *TPAWT* TreadPort Active Wind Tunnel, *XTPAWT* extended TreadPort Active Wind Tunnel

providing objective formalized requirements that indicate exactly how to implement an interface. More practical indications and guidelines to implement some of the listed features with the technology currently available are presented in other works (Hollerbach 2002; Steinicke et al. 2013; Fröhlich and Wachsmuth 2013; Spanlang et al. 2014). In addition to this, currently it is not possible to fully define the requirements expressed by certain features since these constitute open issues and, therefore, further research is needed. For instance, there are several mentions of tracking technology of "sufficient" accuracy or latency that is "not perceivable," but no values are given. These notions of sufficiency and perception are not defined in the framework because research has not found yet all such values. Moreover, acceptable values relating to these issues might change over time (for example, some early papers on visual feedback display cite 100 ms end-to-end latency as being excellent but even at 20 ms people may be able to perceive delay in motion cues). Nevertheless, the framework serves as a starting point toward the definition of requirements for the creation of optimal interfaces. It can be complemented in future work when all the requirements will be defined in a formal, objective way.

Moreover, the proposed list of features aim at guiding VE designers toward improvements in their systems, and this is achieved also by means of comparisons with the systems previous versions. However, it is important to note that such a list has not been conceived to explicitly compare different systems developed by different groups. To achieve such a comparison, an assignment of a weight to each feature would be necessary. Nevertheless, at the moment this seems not feasible due to the fact that it would be a process too much open to interpretations. Future works are needed to investigate thoroughly this issue. Therefore, currently the frameworks are able only to predict that a version of the same system improved with more features fully or partially accomplished would lead to a higher sense of presence compared to that achievable with previous versions.

Finally, it is necessary to note that the framework has been based on considering the most general scenario, i.e., any form of locomotion and a general VE. For specific contexts, not all the features are needed, while others are critically important. For instance, for rehabilitation applications, the features concerning safety are fundamental while those concerning multiple users can be overlooked. Along the same line, the tracking and visual rendering of the parts of the body that can be seen by the user are only necessary for HMD-based systems, not for CAVE-based systems.

In conclusion, it is hoped that this framework can be useful to enable designers and developers of systems for real locomotion in VEs to optimize their simulations both technically and perceptually in order to facilitate the production of strong place and plausibility illusions. Moreover, it is hoped that results of future research in the field of locomotion perception in VEs could allow a more formal and objective definition of all the proposed requirements.

Table 7 Table of scores for display features

System	DF_G_1	DF_G_2.1	DF_G_2.2	DF_G_2.3	DF_G_2.4	DF_G_3.1	DF_G_3.2	DF_G_3.3	DF_G_4.1	DF_G_4.2	DF_G_4.3	DF_G_5.1	DF_G_5.2
SBA	F	P	P	P	A	P	P	P	P	P	P	P	P
XSBA	F	**P**$_{+}$	P	**P**$_{+}$	**P**	P	P	P	P	P	**P**$_{+}$	P	P
CWP	F	P	P	A	A	P	P	P	P	P	P	P	P
XCWP	F	**P**$_{+}$	P	**P**	**P**	P	P	P	P	P	**P**$_{+}$	P	P
TPAWT	F	P	P	P	P	A	P	P	A	P	P	P	P
XTPAWT	F	**P**$_{+}$	P	**P**$_{+}$	**P**$_{+}$	A	P	**P**$_{+}$	A	P	**P**$_{+}$	P	P

System	DF_G_5.3	DF_MR_1	DF_MR_2	DF_MR_3	DF_MR_4	DF_MR_5	DF_MR_6	DF_MR_7	DF_MR_8	DF_MR_9	DF_MR_10	DF_MUR_1	DF_MUR_2
SBA	P	P	P	A	P	P	A	A	A	P	F	A	A
XSBA	P	P	**P**$_{+}$	**P**	**P**$_{+}$	**P**$_{+}$	A	A	A	P	F	A	A
CWP	P	P	A	P	A	P	A	A	A	P	F	A	A
XCWP	**P**$_{+}$	P	**P**	**P**$_{+}$	**P**	**P**$_{+}$	A	A	A	P	F	A	A
TPAWT	P	P	A	P	P	A	A	A	A	P	F	A	A
XTPAWT	**P**$_{+}$	P	**P**	**P**$_{+}$	P	**P**	A	A	A	P	F	A	A

The features improved in the systems extended version are provided in bold

DF display feature, *G* general, *MR* multimodal rendering, *MUR* multiple users rendering, *SBA* shoe-based architecture, *XSBA* extended shoe-based architecture, *CWP* CyberWalk platform, *XCWP* extended CyberWalk platform, *TPAWT* TreadPort Active Wind Tunnel, *XTPAWT* extended TreadPort Active Wind Tunnel

Compliance with Ethical Standards

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References

Barfield W, Zeltzer D, Sheridan T, Slater M (1995) Presence and performance within virtual environments. In: Virtual environments and advanced interface design pp 473–513

Biocca F, Inque Y, Polinsky H, Lee A, Tang A (2002) Visual cues and virtual touch: role of visual stimuli and intersensory integration in cross-modal haptic illusions and the sense of presence. In: Proceedings of presence, pp 410–428

Bruder G, Steinicke F, Bolte B, Wieland P, Frenz H, Lappe M (2012) Exploiting perceptual limitations and illusions to support walking through virtual environments in confined physical spaces. Displays 34(2):132–141

Calvert G, Spence C, Stein B (2004) The handbook of multisensory processes. MIT press, Cambridge

Chertoff D, Schatz S, McDaniel R, Bowers C (2008) Improving presence theory through experiential design. Presence Teleoperators Virtual Environ 17(4):405–413

Chertoff DB, Goldiez B, LaViola JJ (2010) Virtual experience test: a virtual environment evaluation questionnaire. In: Proceedings the IEEE virtual reality conference, pp 103–110

Dinh H, Walker N, Hodges L, Song C, Kobayashi A (1999) Evaluating the importance of multi-sensory input on memory and the sense of presence in virtual environments. In: IEEE virtual reality conference, pp 222–228

Fajen B (2013) Affordance perception and the visual control of locomotion. In: Human walking in virtual environments. Springer, New York, pp 79–98

Fitzpatrick P, Carello C, Schmidt R, Corey D (1994) Haptic and visual perception of an affordance for upright posture. Ecol Psychol 6(4):265–287

Flach J, Holden J (1998) The reality of experience: Gibson's way. Presence Teleoperators Virtual Environ 7(1):90–95

Frissen I, Campos J, Sreenivasa M, Ernst M (2013) Enabling unconstrained omnidirectional walking through virtual environments: an overview of the cyberwalk project. In: Human walking in virtual environments. Springer, New York, pp 113–144

Fröhlich J, Wachsmuth I (2013) The visual, the auditory and the haptic—a user study on combining modalities in virtual worlds. In: Shumaker R (ed) Virtual, augmented and mixed reality. Designing and developing virtual and augmented environments, Lecture Notes in Computer Science, vol 8021. Springer, New York, pp 159–168

Gaver W (1991) Technology affordances. In: Proceedings of the SIGCHI conference on Human factors in computing systems. ACM, New York, pp 79–84

Gibson J (1979) The ecological approach to visual perception. Houghton Miffin, New York

Giordano B, Bresin R (2006) Walking and playing: What's the origin of emotional expressiveness in music? In: Proceedings of the 9th international conference on music perception & cognition, p 436

Giordano B, Visell Y, Yao HY, Hayward V, Cooperstock J, McAdams S (2012) Identification of walked-upon materials in auditory, kinesthetic, haptic and audio-haptic conditions. J Acoust Soc Am 131:4002–4012

Grechkin T, Plumert J, Kearney J (2014) Dynamic affordances in embodied interactive systems: the role of display and mode of locomotion. IEEE Trans Visual Comput Graph 20(4):596–605

Gross D, Stanney K, Cohn L (2005) Evoking affordances in virtual environments via sensory-stimuli substitution. Presence Teleoperators Virtual Environ 14(4):482–491

Hartson R (2003) Cognitive, physical, sensory, and functional affordances in interaction design. Behav Inf Technol 22(5):315–338

Harvey M, Sanchez-Vives M (2005) The binding problem in presence research. Presence Teleoperators Virtual Environ 14(5):616–621

Heeter C (1992) Being there: the subjective experience of presence. Presence Teleoperators Virtual Environ 1(2):262–271

Heeter C (1995) Communication research on consumer vr. Communication in the age of virtual reality, pp 191–218

Hermann T, Hunt A, Neuhoff J (eds) (2011) The sonification handbook. Logos Publishing House, Berlin

Hollerbach J (2002) Locomotion interfaces. In: Handbook of virtual environments: design, implementation, and applications, pp 239–254

Hollerbach J, Xu Y, Christensen R, Jacobsen S (2000) Design specifications for the second generation sarcos treadport locomotion interface. In: Haptics symposium, proceedings of the ASME dynamic systems and control division, vol 69, pp 1293–1298

Hülsmann F, Mattar N, Fröhlich J, Wachsmuth I (2014) Simulating wind and warmth in virtual reality: conception, realization and evaluation for a cave environment. J Virtual Real Broadcast 11(10):1–20

Kulkarni S, Fisher C, Pardyjak E, Minor M, Hollerbach J (2009) Wind display device for locomotion interface in a virtual environment. In: Proceedings of IEEE World haptics conference. IEEE, pp 184–189

Kulkarni S, Minor M, Deaver M, Pardyjak E, Hollerbach J (2012) Design, sensing, and control of a scaled wind tunnel for atmospheric display. IEEE Trans Mechatron 17(4):635–645

Larsson P, Väljamäe A, Västfjäll D, Tajadura-Jiménez A, Kleiner M (2010) Auditory-induced presence in mixed reality environments and related technology. In: The engineering of mixed reality systems. Springer, New York, pp 143–163

Lee K (2004) Why presence occurs: evolutionary psychology, media equation, and presence. Presence Teleoperators Virtual Environ 13(4):494–505

Lepecq J, Bringoux L, Pergandi J, Coyle T, Mestre D (2009) Afforded actions as a behavioral assessment of physical presence in virtual environments. Virtual Reality 13(3):141–151

Li XF, Logan RJ, Pastore RE (1991) Perception of acoustic source characteristics: walking sounds. J Acoust Soc Am 90(6):3036–3049

Maier J, Fadel G (2009a) Affordance based design: a relational theory for design. Res Eng Design 20(1):13–27

Maier J, Fadel G (2009b) Affordance-based design methods for innovative design, redesign and reverse engineering. Res Eng Design 20(4):225–239

Mäkelä K, Hakulinen J, Turunen M (2003) The use of walking sounds in supporting awareness. In: Proceedings of ICAD, pp 144–147

Marchal M, Lécuyer A, Cirio G, Bonnet L, Emily M (2010) Walking up and down in immersive virtual worlds: novel interactive techniques based on visual feedback. In: IEEE symposium on 3D user interfaces, pp 19–26

Mark LS (1987) Eyeheight-scaled information about affordances: a study of sitting and stair climbing. J Exp Psychol Hum Percept Perform 13(3):361–370

McGrenere J, Ho W (2000) Affordances: clarifying and evolving a concept. Graph Interface 2000:179–186

Nordahl R, Serafin S, Turchet L, Nilsson N (2012) A multimodal architecture for simulating natural interactive walking in virtual environments. PsychNology J 9(3):245–268

Oudejans R, Michaels C, Bakker F, Dolné M (1996) The relevance of action in perceiving affordances: perception of catchableness of fly balls. J Exp Psychol Hum Percept Perform 22(4):879

Pastore R, Flint J, Gaston J, Solomon M (2008) Auditory event perception: the source-perception loop for posture in human gait. Atten Percept Psychophys 70(1):13–29

Peck T, Fuchs H, Whitton M (2012) The design and evaluation of a large-scale real-walking locomotion interface. IEEE Trans Visual Comput Graphics 18(7):1053–1067

Pine J, Gilmore J (2011) The experience economy. Harvard Business Press, Boston

Ravaja N, Saari T, Turpeinen M, Laarni J, Salminen M, Kivikangas M (2006) Spatial presence and emotions during video game playing: Does it matter with whom you play? Presence Teleoperators Virtual Environ 15(4):381–392

Regia-Corte T, Marchal M, Cirio G, Lécuyer A (2013) Perceiving affordances in virtual reality: influence of person and environmental properties in perception of standing on virtual grounds. Virtual Real 17(1):1–12

Riva G, Mantovani F, Capideville C, Preziosa A, Morganti F, Villani D, Gaggioli A, Botella C, Alcañiz M (2007) Affective interactions using virtual reality: the link between presence and emotions. CyberPsychol Behav 10(1):45–56

Ruddle R, Lessels S (2009) The benefits of using a walking interface to navigate virtual environments. ACM Trans Comput Human Interact 16(1):5

Schubert T (2009) A new conception of spatial presence: once again, with feeling. Commun Theory 19(2):161–187

Slater M (2002) Presence and the sixth sense. Presence Teleoperators Virtual Environ 11(4):435–439

Slater M (2009) Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. Philos Trans R Soc B Biol Sci 364(1535):3549–3557

Slater M, Usoh M, Steed A (1995) Taking steps: the influence of a walking technique on presence in virtual reality. ACM Trans Comput Human Interact 2(3):201–219

Slater M, Lotto B, Arnold MM, Sanchez-Vives MV (2009) How we experience immersive virtual environments: the concept of presence and its measurement. Anuario de Psicologia 40(2):193–210

Souman J, Robuffo Giordano P, Schwaiger M, Frissen I, Thümmel T, Ulbrich H, De Luca A, Bülthoff H, Ernst M (2011) Cyberwalk: enabling unconstrained omnidirectional walking through virtual environments. ACM Trans Appl Percept 8(4):25

Spanlang B, Normand J, Borland D, Kilteni K, Giannopoulos E, Pomes A, Gonzalez-Franco M, Pérez Marcos D, Arroyo Palacios J, Muncunill X, Slater M (2014) How to build an embodiment lab: achieving body representation illusions in virtual reality. Front Robot AI 1:9

Spence C (2007) Audiovisual multisensory integration. Acoust Sci Technol 28(2):61–70

Spence C (2011) Crossmodal correspondences: a tutorial review. Atten Percept Psychophys 73(4):971–995

Steinicke F, Visell Y, Campos J, Lécuyer A (2013) Human walking in virtual environments: perception, technology, and applications. Springer, New York

Turchet L (2014) Custom made wireless systems for footstep sounds synthesis. Appl Acoust 83:22–31

Turchet L, Serafin S (2014) Semantic congruence in audio-haptic simulation of footsteps. Appl Acoust 75(1):59–66

Turchet L, Nordahl R, Berrezag A, Dimitrov S, Hayward V, Serafin S (2010) Audio-haptic physically based simulation of walking on different grounds. In: Proceedings of IEEE international workshop on multimedia signal processing, IEEE Press, pp 269–273

Turchet L, Nilsson N, Serafin S (2012) Inside the boundaries of the physical world: audio-haptic feedback as support for the navigation in virtual environments. Haptics: Perception, Devices, Mobility, and Communication, vol 7282. Lecture Notes in Computer Science, Springer, Berlin, pp 577–588

Usoh M, Arthur K, Whitton M, Bastos R, Steed A, Slater M, Brooks Jr F (1999) Walking > walking-in-place > flying, in virtual environments. In: Proceedings of the 26th annual conference on computer graphics and interactive techniques, pp 359–364

Van Toller S, Dodd G (eds) (1988) Perfumery: the psychology and biology of fragrance. Chapman & Hall, London

Van Toller S, Dodd G (eds) (1992) Fragrance: the psychology and biology of perfume. Chapman & Hall, London

Visell Y, Law A, Cooperstock JR (2009) Touch is everywhere: floor surfaces as ambient haptic interfaces. IEEE Trans Haptics 2:148–159

Warren W (1984) Perceiving affordances: visual guidance of stair climbing. J Exp Psychol Hum Percept Perform 10(5):683

Warren W, Whang S (1987) Visual guidance of walking through apertures: body-scaled information for affordances. J Exp Psychol Hum Percept Perform 13(3):371–383

Yanagida Y, Kawato S, Noma H, Tomono A, Tesutani N (2004) Projection based olfactory display with nose tracking. In: IEEE virtual reality conference, IEEE, pp 43–50

Zahorik P, Jenison R (1998) Presence as being-in-the-world. Presence Teleoperators Virtual Environ 7(1):78–89

Zanbaka C, Lok B, Babu S, Ulinski A, Hodges L (2005) Comparison of path visualizations and cognitive measures relative to travel technique in a virtual environment. IEEE Trans Visual Comput Graph 11(6):694–705

Zanotto D, Turchet L, Boggs E, Agrawal S (2014) Solesound: towards a novel portable system for audio-tactile underfoot feedback. In: Proceedings of the 5th IEEE international conference on biomedical robotics and biomechatronics, IEEE, pp 193–198