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Feedback, Affordances, and Accelerators for Training Sports in Virtual Environments

Abstract

The use of virtual environments (VE) for training sports is quite natural when considering strategic or cognitive aspects. Using VE for sensorimotor training is more challenging, in particular with the difficulty of transferring the task learned in the virtual world to the real. Of special concern for the successful transfer is the adequate combination of training experience protocols and the delivery modes of multimodal feedback. Analyzing feedback in terms of information exchange, this work discusses different feedback combinations and their application to virtual reality training of rowing skills.

1 Introduction

In the general context of developing virtual environments (VE) for training, a special opportunity for exploiting the advancement of visual and haptic technologies exists in the context of sports training. In the previous days of computer technology, training environments were obtained by providing offline and online information about athlete performance in the form of biofeedback (Liebermann & Breazeal, 2007), or transfer from the video game training context to performance at the real task (Rosser et al., 2007). The recent improvement in visualization, motion capture, and computing power in general has paved the way for the development of simulation VE for training sensorimotor components of sports (Hasegawa et al., 2006; Bailenson et al., 2008; Bideau et al., 2010). For example, Bailenson (Bailenson et al., 2008) discusses the effectiveness of interactivity in training a physical task connected to tai chi based on an immersive display of recorded videos. For a general discussion about feedback, human-computer interaction, and classic training, see Menezes de Oliveira e Paiva (2003).

Although technology has greatly improved, multiple design challenges need to be addressed. One challenge is the identification of specific elements that compose sport skills and which can benefit from training in VE. Another challenge relates to identifying the best combination of training protocols and multimodal feedback that can be employed to improve these skill elements in a given task on the training platform. Finally, the transfer from VE training to real training is a decisive challenge that needs to be considered for positive evaluation of VE training platforms.

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The present paper focuses specifically on the second of the above challenges, namely, the selection of the optimal combination of training protocol and multimodal feedback. Drawing upon the concept of affordances (Gibson, 1977), this paper highlights the best combination of protocol and feedback to constitute accelerators on the VE training platform. This analysis is illustrated in the context of an indoor rowing training system on which different solutions can be tested (Ruffaldi, Filippeschi, Frisoli, Sandoval, et al., 2009). Our analysis reveals the importance of functional and action fidelity (Riccio, 1995; Stoffregen, Bardy, Smart, & Pagulayan, 2002; Mania, Wooldridge, Coxon, & Robinson, 2006) among the possibilities offered by VE technologies during sport training, which contrast with the improvements of subjective or experience fidelity classically put forward when improvement of VE technology is addressed.

2 Feedback for Virtual Environments

The interaction loop between the user and the VE can be described in terms of exchanges between entities, in particular the real user, the real environment consisting of real objects and humans beings, and the virtual environment with virtual objects and virtual humans. This entity-interaction model can be specialized for the context of training by adding the trainer (the trainer can be a real or a virtual entity). Training the user based on feedback can be mediated by any of the entities of the real and virtual environment, and this feedback can be considered as a form of information exchange (Wickens & Holland, 1999). In this section, we present different dimensionalities of feedback used in VE for training, and we organize them along key aspects of the information exchange. For describing and organizing the feedback we will cover several questions related to information exchange, in particular *which* information is exchanged, *how* information is exchanged and, most importantly for training, *when* information is delivered and its relationship with time. The first group of feedback descriptors captures the information content and its semantics, and we will term them the *meaning* category. The second group instead looks at how information is mediated to the user both in terms of perceptual channel and environment entity (real/virtual) channeling the information. We will call this group *medium*. Finally, the third group covers the detailed *format* of the feedback with mostly aspects associated with time. The following is a brief list of the three categories of feedback descriptors.

Meaning

- Meaning. Informative, of error or performance, and guidance.

Medium

- Modality. The perceptual channel used for providing feedback.
- Mediator. The entity that mediates the information.

Format

- Dynamics. Feedback provided statically or dynamically.
- Concurrency. Feedback provided in sync with the action or out of sync with the action.
- Frequency. The frequency of the feedback provided during training.
- Continuity. The continuous or discrete nature of the dependent variable.
- Adaptation. Feedback provided (in-)dependently of the trainee's level of expertise.

In the following paragraph, we describe the above descriptors for each category highlighting how they can potentially contribute to accelerate the acquisition of skill. For each descriptor, we refer to the main results when available and the respective technology components. This short survey is not intended to be exhaustive, but to target the reader's attention to important issues still to be addressed in virtual reality training situations. Specific scenarios during virtual training in rowing are thus proposed in the following section.

2.1 Meaning Category

2.1.1 Meaning. The meaning of the information provided by the feedback is crucial for the design of a whole learning system because it describes how this feedback directs and shapes the behavior of the trainee. The most typical stimuli used in VEs are associated with the simulation of physical properties of the world itself, typically expressed in the form of visual properties of surfaces, textures, colors, shadings, and more generally of the environment with which the agent interacts. The role of realism in VE tasks and learning is still an open issue (Vignais et al., 2009). Knowledge of performance (KP) and knowledge of results (KR) are two forms of augmented feedback given, for example, verbally or visually in VR at the end of a performance, known to contribute to solidifying learning (Adams, 1987). KP contains information about the nature of the movement pattern produced during the performance (e.g., including parts of the skill performed incorrectly and errors), and KR is information about the outcome of the performance (Schmidt & Lee, 2005). *Informative* feedback is the most widely used. Informative feedback gives the user information about given parameters for providing the user KP or in some cases KR (Schmidt & Lee, 2005). Typically, informative feedback is used either for noting errors to the user, during or after the action, or for giving the user a score. *Guidance* feedback provides directions to the user about the next action to be performed, or constraint for its motion. Physical assistance is an example of feedback which acts as a guidance for leading the user's next movement (Morris, Tan, Barbagli, Chang, & Salisbury, 2007). Feedback can also guide the attentional focus of the user while performing a task. As an example, Wulf and Shea (1999) showed how the same visual feedback combined with appropriate instructions could either internally or externally lead the user's attentional focus.

2.2 Medium Category

The medium descriptor defines the way the feedback interacts with the user and how the feedback is integrated with the VE.

2.2.1 Modality. This descriptor refers to the perceptual channel(s) used to carry feedback information. The decision about which channel to use for conveying information depends on the available technology, but more importantly on the role of the modalities, the task execution, and the type of information.

In many circumstances, the combination of several modalities can be used (e.g., Virsu, Oksanen-Hennah, Vedenpaa, Jaatinen, & Lahti-Nuuttila, 2008), often producing better learning performance than unimodal feedback (Morris et al., 2007), but not always (see Stoffregen & Bardy, 2001, for a theoretical treatment). Multimodal feedback from different modalities can be congruent (i.e., providing the same information in different perceptual channels), or incongruent (i.e., providing different and sometimes contradictory information in different modalities). The large literature related to unimodal versus multimodal training using VE technology gives mixed results. This is in general the point about the combination of multiple basic feedback that should be correctly coordinated for reducing the possibility of cancelling effects.

2.2.2 Mediator. This feedback descriptor captures a higher-level mode of feedback deployment. In particular, it tries to distinguish between direct feedback, for example, on-screen or audio messages, compared to more complex behaviors that are presented in the virtual environment. Basic informative feedback coming from the trainer can be delivered on-screen, while other feedback can be embodied in VE entities, for example, feedback coming from virtual humans. If we use a virtual human for guiding the user, we can modify the behavior of the virtual human as a form of feedback: for instance, making an opponent more skilled can be seen not only as a stimulus, but also as a feedback about the outcome of the user's performance. The role of a virtual human is important in VE and has been tested in human behavioral studies (e.g., Kelso, de Guzman, Reveley, & Tognoli, 2009). For a discussion about technical features of virtual humans in VE, see Gilles and Spanlang (2010).

An important aspect related to the mediator is the immersive nature of the information medium. When dealing with a VE-based training system, it is important to distinguish between feedback given inside the VE from feedback provided externally. This choice affects the immersion of the experimental setup, and, as argued by Slater (Slater, Linakis, Usoh, & Kooper, 1996), for some tasks improved immersion leads to a better task performance. In addition, the unsolved debate about the

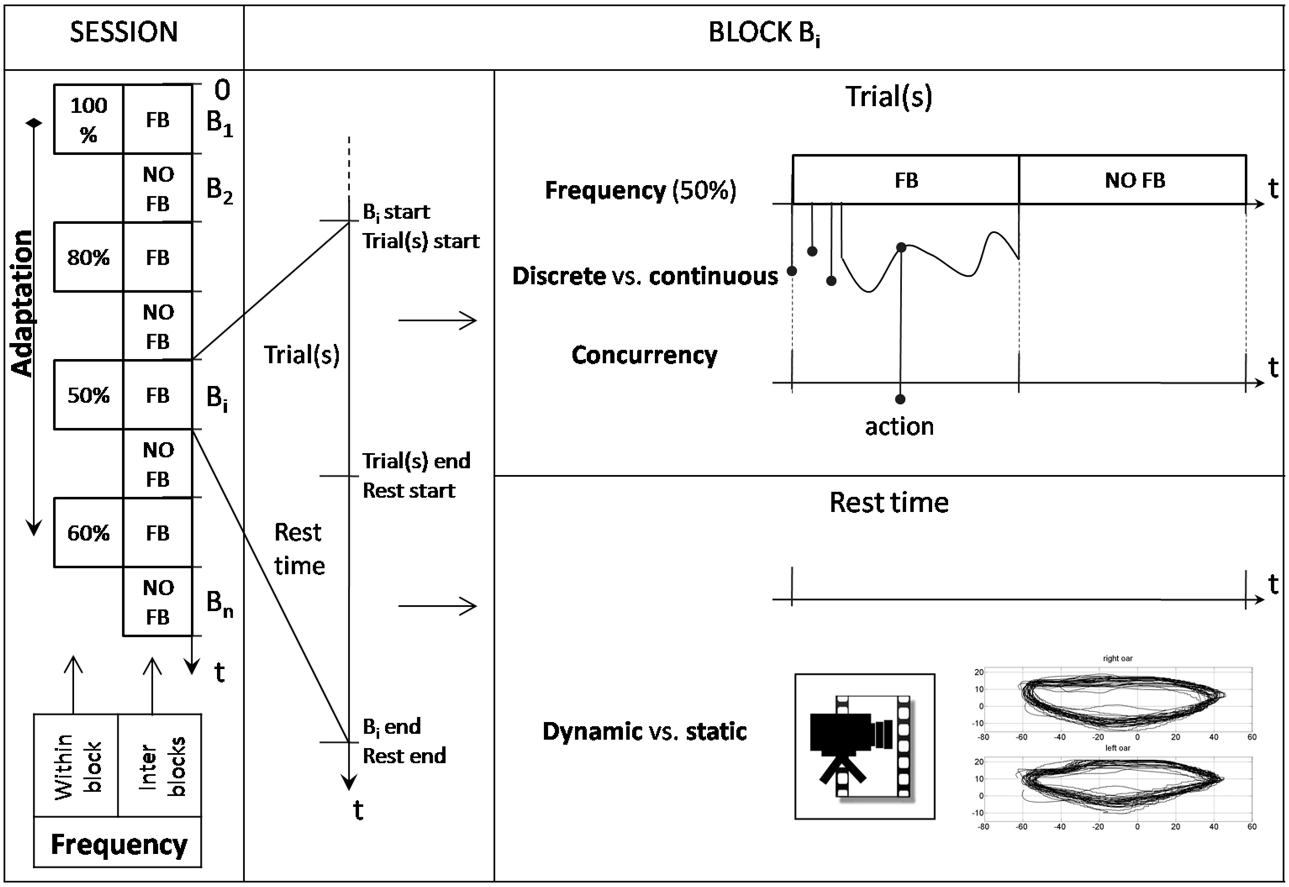

Figure 1. *Diagram presenting an example of the format feedback descriptors inside the typical phases of sport training. On the left, the session is decomposed in blocks, containing both trials and resting phases. During the trial, the feedback is provided with some frequency cases, online or off-line with respect to the action and associated to a continuous or discrete variable. During the resting period, the feedback (off-line delayed) can be provided dynamically or statically. Finally, the way the feedback is modulated along the session is controlled by adaptation.*

relation between sense of presence and task performance (Stanney, Mourant, & Kennedy, 1998) constrains the experiment designer to be careful when adopting feedback known to alter the sense of presence.

2.3 Format Category

This category describes the formatting of the feedback, with specific focus on how the feedback is deployed along the different phases of the training session. The diagram in Figure 1 shows how the different descriptors of the format act within sessions, blocks, and trials.

2.3.1 Dynamics. Feedback can be provided as a single static representation of the meaning, or instead as a dynamic representation of it. For example, when the goal is to present to the trainee the trajectory of the motion at the end of a training block, this information can be presented statically with a single image showing the various paths, or instead as an animated path expressing motion, for example, changes over time. A discussion about static and dynamic stimuli depending on the expertise level can be found in Jarodzka et al. (Jarodzka, Scheiter, Gerjets, & van Gog, 2010). The use of dynamic and static representations is an important issue when establishing how to convey information to the trainee (see Park & Hopkins, 1992). In a recent experiment, Imhof, Scheiter, and Gerjets (2009) showed, for example, the effectiveness of realistic dynamic displays for locomotion pattern recognition. It is worth noting that dynamics are different from continuity. As a simple example, consider a hammer game in an amusement park. In this game, you hit a paddle with a hammer with as much force as you can and then some lights turn on showing the applied force. Lights turn on from the bottom to the top and then stay on for a while. This is a discrete feedback (distinct levels of lights) showing dynamic and then static behavior. Dynamic representations are often used with concurrent feedback (e.g., Wulf & Shea, 1999), whereas static representations are more suitable for focusing on specific aspects (e.g., a point of a trajectory) or for providing the user with a summary or synthetic information about the performance (e.g., the plot of the performed trajectory against the benchmark trajectory, or a score after a game).

2.3.2 Concurrency. Concurrency expresses the distinction between feedback provided during the execution of a task element (online concurrent), just after it has been performed but still within the training session (off-line) or after the training session (delayed off-line). Whereas online delayed feedback has been shown to be more effective for simple skill performance and learning (Vander Linden, Cauraugh, & Greene, 1993; Winstein et al., 1996), concurrent feedback is more effective for complex skills (Wulf & Shea, 2002). In any case, concurrency is a fundamental feature for developing the training scenario and it is the natural choice in the context of VE technologies.

2.3.3 Adaptation. This feature captures the adaptive nature of the designed feedback with respect to the trainee's level (Huegel, Celik, Israr, & O'Malley, 2009). Information about the ongoing action and performance can indeed be independent of trainee's level of expertise, or modulated to integrate the sensorimotor and cognitive capacities of the trainee. Classical learning rules imply that maximizing learning requires an optimal distance between the learner capacities and the task demand. The results obtained by Huegel confirm that adaptive behavior improves the learning rate (Huegel et al., 2009; Winstein & Schmidt, 1990).

2.3.4 Continuity. This feature relates to the variable or information source used for generating the feedback; in particular, either discrete or continuous. When motion-related feedback is concerned, computing the error with respect to a reference trajectory along the entire path (continuous feedback) can be an interesting solution. Alternately, selecting only specific salient points (discrete feedback) may also be adequate, and the decision depends mostly on the focus of the trained skill. An example of real discrete information with an interesting format is the pacing indicator used in rowing with real boats. This digital display shows, using the visual modality, performance information, presenting discrete values of speed dynamically updated after every stroke.

The feedback characteristics discussed above are well known in the motor learning literature (see Schmidt & Lee, 2005, for a review), and need to be considered carefully when designing learning protocols. As indicated, however, they are rarely taken into account in a global way when multimodal VE training situations are designed. The suggested approach for dealing with them is to start from the meaning of the feedback, then identify the mediator of such a feedback, then select the proper modality (depending also on the overall VE perceptual stimulation available to the user), and finally complete the feedback creation by selecting the different aspects from the format category. The selection of the mediator can be performed by adopting the concept of affordances. As discussed in the following section, this allows the research to characterize and describe the entities in the VE.

3 Affordances

Another fundamental yet complementary aspect of interactivity in real and virtual environments needs to be considered for developing efficient multisensory training simulators: affordances. Affordances are opportunities for action (Gibson, 1977; Warren, 1984). Affordances constrain what behaviors are possible in a given situation, what behaviors are easy or hard, efficient or inefficient, and so on. Given their influence on behavior, it is important for humans interacting with technology to know about the affordances that are available to them (e.g., Norman, 1988). Objects or events can offer various affordances; a bottle, for instance, can afford grasping, filling, or drinking. Importantly, affordances are different for novices and for experts; that is, behaviors that are possible for experts may not be possible for novices. More generally, nonlinear changes in behavior during skill acquisition and transfer are accompanied by corresponding changes in relevant information used to control finer and more complex behaviors (e.g., Bardy & Laurent, 1998).

In the virtual world, virtual objects can offer digital affordances, that is, capabilities expressed by a digital element, often but not always inherited from the real world by means of some metaphor. A button on a computer screen typically affords *pushing*, while a scroll bar affords dragging, but this requires some previous knowledge about the use of scroll bars. In VR situations, care should be taken with the transfer from real affordances to digital affordances because they may have different (and negative) consequence on behavior (Slater, Perez-Marcos, Ehrsson, & Sanchez-Vives, 2008; Slater, 2009). In the second part of the article devoted to rowing, we will illustrate how digital affordances can be implemented in the context of a rowing race.

4 Accelerators

We have described above the role played by feedbacks and affordances during skill performance and its acquisition in real and virtual environments. Here we discuss their role in the context of training. A learning accelerator is the combination of training protocols and an articulated set of capturing, analysis, and feedback sent to the user, aimed at improving and shortening the learning process. The ways the training system can influence and/or guide the user behavior can be grouped into three categories that reflect how the information about the task is manipulated: first, augmentation, which introduces more information than in the real task; next, simplification, which reduces information and complexity; and finally, variability, which varies the information provided during the execution of the task and that varies the way that the task's parts are performed. We will discuss below these different categories and specific cases related to the literature.

4.1 Augmentation

This category refers to the ways the training experience is enriched with respect to the real situation. It involves informative feedback, such as KR or KP, task enrichment, such as providing distances between objects in a VE, or as using transparency for showing hidden objects. Augmentation is well known to be very effective for learning; furthermore, in the case of augmented feedback, there is lot of evidence that learning does not occur without it.

The first type of augmentation is information, which is the most typical accelerator that gives the trainee information about his or her performance or about the result of an action with respect to the task's goal. It is highly associated with the feedback of informative meaning, as discussed above.

The second type of augmentation is correction, which is commonly applied when the trainee receives online information about the performance being produced relative to the target performance. This information can be given by means of continuous feedback or alternatively by spot feedback such as discrete vibrations notifying the presence of a given error (e.g., Ruffaldi, Filippegchi, Frisoli, Sandoval, et al., 2009). A discussion about the effect of error augmentation in training can be found in Patton (Patton, Stoykov, Kovic, & Mussa-Ivaldi, 2006).

Finally, the third example of augmentation is task enrichment. Enrichment relates to the introduction of feedback giving more information to the user than reality would give him or her. A good example of this accelerator category is the use of transparency for showing occluded objects. In some ways, this accelerator can be associated with the information accelerator, depending on the way the enrichment is achieved. When there is no interpretation of the performance value, we can consider it simply as task enrichment.

4.2 Simplification

An accelerator belongs to the simplification category when it tries to make the user perform the task in an easier way with respect to the way the task is performed in the real world. The most well-known task simplification is a reduction of the degrees of freedom. Simplification of a task covers several elements of training (Lane, 1987): *segmentation* means that sequential elements are practiced separately, *fractionation* means that simultaneous elements are practiced separately, and finally, *proper simplification* means to practice a reduced subset of the task in terms of scope. Minimally, task simplification can be seen as a reduction of the number of degrees of freedom (DOF) involved. DOFs can be of mechanical origin—for example, reduction in the dimensions along which the movement takes place or in the number of joints—but they can also be at the task level, such as a reduction of the number of subgoals. This simplification is powerful but needs to be associated with an adaptive feedback in most cases. Examples of a family of accelerators can be the reduction of (virtual) gravity, the introduction of viscosity in specific tasks, tremor reductions, or motion scaling. Guidance feedback can be considered a form of simplification, in particular in the case of virtual fixtures. Guidance relates to information along a given direction, both at the level of cognition (e.g., an arrow indicating the direction to go), and sensorimotor exchanges with the virtual environment, such as the case of virtual fixtures. Haptic guidance has been shown to be effective (Marchal-Crespo, McHughen, Cramer, & Reinkensmeyer, 2010) in younger, less-skilled participants, allowing them to avoid large errors.

4.3 Variability

Variability involves the changes in the training environment aimed at forcing the user to leave a stabilized but novice behavior and move toward a transitory unstable expert behavior (e.g., Faugloire, Bardy, & Stoffregen, 2009; Zanone & Kelso, 1992). With this approach, the user learns a given task by receiving variations at different stages. The first stage, when applicable, is often the variation in timing, corresponding to slowing down or speeding up the movement performed (Erev-Yehene, Gopher, Melakin, Lippi, & Avizzano, in preparation). Changes in movement velocity have proven to be efficient at early stages of learning (Braun, Aertsen, Wolpert, & Mehring, 2009). Another important and well-documented effect is the large advantage of variable practice over constant practice in real (e.g., Yao, DeSola, & Bi, 2009) and virtual/distorted environments (e.g., Mulavara, Cohen, & Bloomberg, 2009), specifically at early stages of learning (e.g., Schmidt & Lee, 2005). The exploration of the space of cases should make the user more adaptable to the different conditions. The voluntary introduction of errors in the perception-action loop is efficient because it induces new responses by the trainee. There are several ways that variability can be accomplished: the first one, when applicable, is the variation of timing, imposing slower and faster conditions of practice. Then we have practice variability, that is, differentiating with respect to various practice conditions (see Wulf & Schmidt, 1997; Lai & Shea, 1999; Williams & Hodges, 2004). Finally, we can also use the purposeful introduction of error conditions that can induce new responses from the user.

5 A Virtual Rowing Training System Using Feedback, Affordances, and Accelerators

The SPRINT (Ruffaldi, Filippeschi, Frisoli, Avizzano, et al., 2009) rowing training system allows the user to row in a VE exerting motion patterns that are similar to the ones produced during outdoor and indoor rowing. By means of an analysis of the rowing gesture, SPRINT adaptively trains the user on different aspects of the rowing skill. The system, as shown in Figure 2, is characterized by a mechanical platform that, by means of a pair of fans, produces a force feedback to the user equivalent to the one provided by real rowing (Filippeschi, Ruffaldi, Frisoli, Avizzano, et al., 2009). For a different approach to rowing simulation, see von Zitzewitz et al. (2008). The sensing components of the platform capture various aspects of the athletic gesture, which are used to control the visuo-vibro-tactile feedback inherent to the platform. In particular, the rowing VE is pre-

Figure 2. *SPRINT system configured inside an immersive visualization system.*

sented on a display (a traditional LCD, or an immersive display, depending on the configuration), and in this VE various types of 2D, 3D, or behavioral feedback can be triggered depending on the training protocol. The visual part is paired by vibrotactile bracelets used for triggering guidance or error feedback (Ruffaldi, Filippeschi, Frisoli, Sandoval, et al., 2009). The software architecture is based on the integration of the XVR framework (Carrozzino, Tecchia, Bacinelli, Cappelletti, & Bergamasco, 2005) for the graphics and MATLAB/Simulink for real-time capturing, and on the analysis and the training protocol implementation.

As part of the design phase of the SPRINT system, we have decomposed the rowing task in components following hierarchical task analysis (Shepherd, 1985), then identified, with the collaboration of coaches and knowledge from rowing manuals, the most important aspects of the rowing task, the typical errors, and the standard training protocols. From this analysis we have identified three relevant scenarios for the proposed training system: technique optimization, energy management, and team coordination. For each of these scenarios, we have identified the most important aspects to be trained, and in parallel, the basic components of the skill that were relevant to be analyzed and improved, such as procedure and coordination. The result of this analysis has brought to the definition of one or more training protocols in each scenario associated to selected accelerators and based on specific multimodal feedback (Ruffaldi, Filippeschi, Avizzano, & Bergamasco, 2010).

6 Feedback for Rowing Training

The following are examples of feedback currently being adopted in SPRINT, as selected after the analysis discussed in Section 4. Table 1 synthesizes the following descriptions using the taxonomy described in Section 2.

6.1 Technique Optimization Scenario

6.1.1 Trajectory Training. For training specific trajectory patterns, several approaches can be employed, and some of them have been tested elsewhere (Ruffaldi, Filippeschi, Frisoli, Sandoval, et al., 2009). In particular, a possible approach, depicted in Figure 3, uses the visual channel for guidance information, presenting the reference position of the hand immersed in the VE, and concurrent with the motion of the user. The frequency of this feedback is 100%: it is always provided during training trials.

An alternative approach is to adopt a vibrotactile feedback, triggered on error performed by the user as shown in Figure 4 (see also Bloomfield & Badler, 2008; and Lindeman, Page, Yanagida, & Sibert, 2004). This solution is dynamic and in real time, as well, and it is continuously provided to the user. The frequency of the feedback is 100%. We are testing these two types of feedback on the same protocol, and they are meant to be effective both in retention and in transfer tests. Furthermore, the combination of the two types of feedback (visual and vibrotactile given at the same time) seems to be more effective for transfer than the two modalities taken alone (Ruffaldi, Filippeschi, Frisoli, Sandoval, et al., 2009 and Ruffaldi, Filippeschi, Frisoli, Avizzano, et al., 2009). However, the results are still too preliminary to draw a final conclusion.

In the context of the same protocol, we recently introduced two types of off-line visual feedback displaying, after the execution of the task, the performed trajectory against the target trajectory. In this case, the role of the feedback was to give a knowledge of the result, and we

Table 1. *Descriptors of Feedback Discussed and the Feedback Adopted in the SPRINT System*

	Pacing	Visual trajectory	Vibrotactile trajectory	Off-line trajectory	Energy strategy	Team coordination	Trajectory optimization
Meaning	Performance	Guidance	Error	Performance	Performance	Error	Informative
Modality	Visual	Visual	Vibrotactile	Visual	Visual	Visual	Visual/haptic/audio
Mediator	External sound source	Immersive trajectory	On wrist bracelet	On-screen Plot	Virtual human	Virtual human	On-screen message and external sources
Dynamics	Dynamic	Dynamic	Dynamic	Static and Dynamic	Dynamic	Dynamic	Static
Concurrency	Online (stroke)	Online	Online	Delayed Offline	Online	Online	Online
Frequency	100%	100%	100%	50%	25–100%	100%	100%
Continuity	Discrete	Continuous	Continuous	Continuous	Continuous	Continuous	Discrete
Adaptation	None	None	None	None	Partial	Partial	None

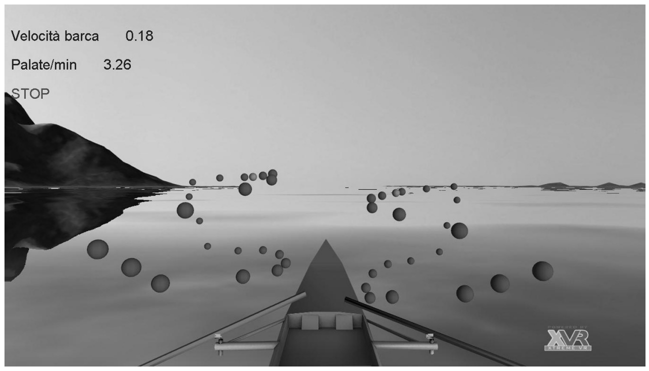

Figure 3. *Training trajectory by means of visual feedback.*

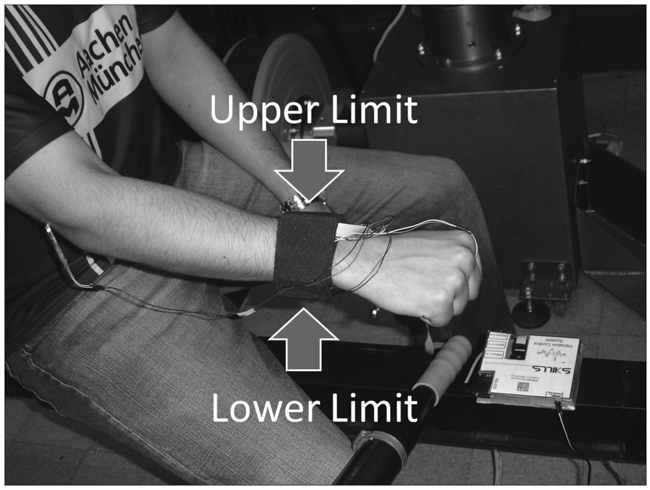

Figure 4. *Vibrotactile feedback for inducing corrections in the trajectory.*

distinguished between static (whole trajectory presented at one time) and dynamic presentation (playback of a performed trajectory window moving around the target). Since this information was off-line, it was not presented in an immersive way, and involved no adaptation. For trajectory training, the six possible combinations of online and off-line feedback are now being tested in order to establish the most effective accelerator.

6.1.2 Trajectory optimization training. This last example of the training scenario aims at training the user for the refinement of rowing technique. In this scenario, the tested accelerator is composed of an analysis

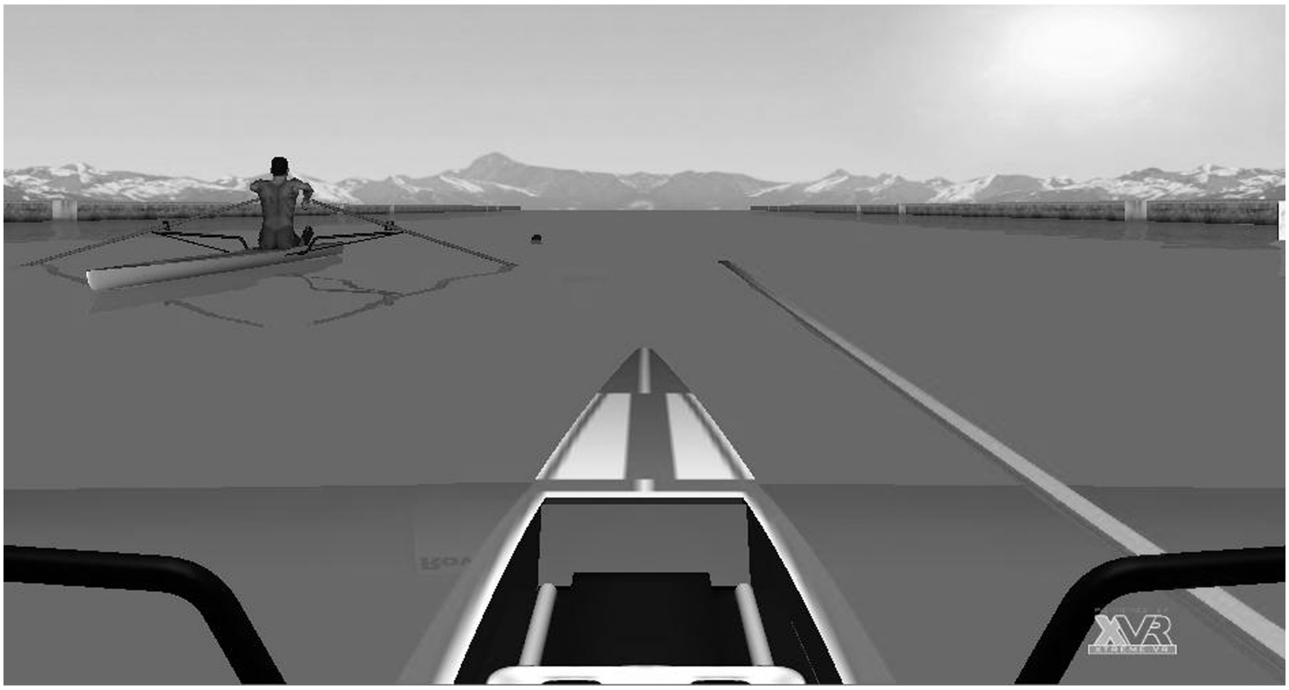

Figure 5. *Example of distance feedback for energy training.*

part that led to the identification of experts' benchmark positions (four positions were chosen) and their variability. The four positions are marked in the VE by means of four bars that can be used as feedback by turning their color either to green or red according to the correctness of the gesture. An auditory feedback can also be provided as a high or low frequency tone which occurs in case of error. As a last part, a guiding haptic stimulus is given to provide boundaries for the possible trajectory. Several combinations of VE, feedback, and stimulus are being tested for the effectiveness of the accelerator. In this case, the bar feedback is informative, since it gives KR as an error with respect to the task, its modalities are visual and immersive, it is also concurrent, discrete, not adaptive, and provided with 100% frequency.

6.2 Energy Management

6.2.1 Energy Strategy Based on a Virtual Human. With the objective of training for energy management—providing information about how to correctly spend energy resources during the race—we are using a virtual reference opponent to be followed at a given constant distance. The speed of the opponent is manipulated and the distance between the boat and the opponent is expressed by means of a visual arrow immersed in the environment, as shown in Figure 5. This is a unique example of the combination of visual and behavioral modality, with concurrent feedback. In the current instantiation, the protocol has been implemented with adaptation of feedback to the level of the athlete, instead of adopting the typical baseline. The frequency of the feedback varies with time: in the first training session it is 100% (i.e., 2000 m over a 2000 m race); then it is reduced.

6.3 Team Coordination Scenario

6.3.1 Team Coordination Based on a Virtual Human. Another aspect of the rowing addressed by SPRINT is team rowing, for which being coordinated with one's partner is a key component of performance. Interpersonal coordination (e.g., Varlet, Marin, Lagarde, & Bardy, 2010) can be improved by exercise, and can be

Figure 6. *Coordination feedback example.*

trained using specific feedback. On the SPRINT system, we follow the approach of using the body of the peer for training the coordination behavior of the user, as shown in Figure 6. This is an example of the use of behavioral and visual modalities, adopted in particular as error conditions for deficient behavior. This feedback is inherently dynamic and immersive with a concurrent continuous response.

7 Conclusions

The possibilities offered by VE have yet to be explored in particular for the connection with complex sensorimotor behaviors, such as those encountered in sport. This paper proposed to contribute to this exploration by pointing out the structural elements for designing adequate training environments. We have taken the case of the proposed rowing system for presenting how, on a single platform, different parts of the original task and different approaches can be pursued. The presented feedback for most of the possibilities have yet to be evaluated. The transfer of effective techniques from real training to virtual training needs to be taken on with caution, and the transfer from virtual training to real training should also be done with care.

The evaluation agenda presented above, together with the test of other accelerators, is at a burgeoning stage. The immediate next challenge is understanding the methodology for validating the above families of accelerators in the transfer from the real environment to VE and from VE to the real environment.

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References

Adams, J. A. (1987). Historical review and appraisal of research on the learning, retention, and transfer of human motor skills. *Psychological Bulletin, 101*(1), 41–74.

Bardy, B. G., & Laurent, M. (1998). How is body orientation controlled during somersaulting? *Journal of Experimental Psychology: Human Perception and Performance, 24*(3), 963.

Bailenson, J., Patel, K., Nielsen, A., Bajscy, R., Jung, S.-H., & Kurillo, G. (2008). The effect of interactivity on learning physical actions in virtual reality. *Media Psychology, 11*(3), 354–376. doi: 10.1080/15213260802285214.

Bideau, B., Kulpa, R., Vignais, N., Brault, S., Multon, F., & Craig, C. (2010). Using virtual reality to analyze sports performance. *IEEE Computer Graphics and Applications, 30*(2), 14–21.

Bloomfield, A., & Badler, N. I. (2008). Virtual training via vibrotactile arrays. *Presence: Teleoperators and Virtual Environments, 17*(2), 103–120.

Braun, D. A., Aertsen, A., Wolpert, D. M., & Mehring, C. (2009). Motor task variation induces structural learning. *Current Biology, 19*(4), 352–357.

Carrozzino, M., Tecchia, F., Bacinelli, S., Cappelletti, C., & Bergamasco, M. (2005). Lowering the development time of multimodal interactive application: The real-life experience of the XVR project. *Proceedings of the 2005 ACM SIGCHI International Conference on Advances in Computer Entertainment Technology,* 270–273.

Erev-Yehene, V., Gopher, D., Melakin, P., Lippi, V., & Avizzano, C. A. (In preparation). Speed manipulation in training virtual juggling.

Faugloire, E., Bardy, B. G., & Stoffregen, T. A. (2009). (De)stabilization of required and spontaneous postural dynamics with learning. *Journal of Experimental Psychology: Human Perception and Performance, 35*, 170–187.

Filippeschi, A., Ruffaldi, E., Frisoli, A., Avizzano, C. A., Varlet, M., Marin, L., et al. (2009). Dynamic models of team rowing for a virtual environment rowing training system. *The International Journal of Virtual Reality, 4*(8), 19–26.

Gibson, J. J. (1977). The theory of affordances. In R. Shaw & J. Bransford (Eds.), *Perceiving, acting, and knowing: Toward an ecological psychology* (pp. 67–82). Hillsdale, NJ: Erlbaum.

Gillies, M., & Spanlang, B. (2010). Comparing and evaluating real time character engines for virtual environments. *Presence: Teleoperators and Virtual Environments, 19*(2), 95–117.

Hasegawa, S., Toshiaki, I., Hashimoto, N., Salvati, M., Mitake, H., Koike, Y., et al. (2006). Human-scale haptic interaction with a reactive virtual human in a real-time physics simulator. *Computers in Entertainment, 4*(3), 9. doi: 10.1145/1146816.1146831.

Huegel, J. C., Celik, O., Israr, A., & O'Malley, M. K. (2009). Expertise-based performance measures in a virtual training environment. *Presence: Teleoperators and Virtual Environments, 18*(6), 449–467.

Imhof, B., Scheiter, K., & Gerjets, P. (2009). Realism in dynamic, static-sequential, and static-simultaneous visualizations during knowledge acquisition on locomotion patterns. *Proceedings of the 31st Annual Conference of the Cognitive Science Society*, 2962–2967.

Jarodzka, H., Scheiter, K., Gerjets, P., & van Gog, T. (2010). In the eyes of the beholder: How experts and novices interpret dynamic stimuli. *Learning and Instruction, 20*(2), 146–154.

Kelso, J. A. S., de Guzman, G. C., Reveley, C., & Tognoli, E. (2009). Virtual partner interaction (VPI): Exploring novel behaviors via coordination dynamics. *PloS One, 4*(6).

Lane, N. E. (1987). *Skill acquisition rates and patterns: Issues and training implications.* New York: Springer-Verlag.

Lai, Q., & Shea, C. H. (1999). Bandwidth knowledge of results enhances generalized motor program learning. *Research Quarterly for Exercise and Sport, 70*, 79–83.

Lieberman, J., & Breazeal, C. (2007). Development of a wearable vibrotactile feedback suit for accelerated human motor learning. *IEEE International Conference on Robotics and Automation,* 4001–4006.

Lindeman, R. W., Page, R., Yanagida, Y., & Sibert, J. L. (2004). Towards full-body haptic feedback: The design and deployment of a spatialized vibrotactile feedback system. *Proceedings of the ACM Symposium on Virtual Reality Software and Technology,* 149.

Marchal-Crespo, L., McHughen, S., Cramer, S. C., & Reinkensmeyer, D. J. (2010). The effect of haptic guidance, aging, and initial skill level on motor learning of a steering task. *Experimental Brain Research, 201*(2), 209–220.

Mania, K., Wooldridge, D., Coxon, M., & Robinson, A. (2006). The effect of visual and interaction fidelity on spatial cognition in immersive virtual environments. *IEEE Transactions on Visualization and Computer Graphics,* 396–404.

Menezes de Oliveira e Paiva, V. L. (2003). Feedback in the virtual environment. *PsychNology Journal, 1*(3), 256–282.

Morris, D., Tan, H., Barbagli, F., Chang, T., & Salisbury, K. (2007). Haptic feedback enhances force skill learning. *Proceedings of the 2007 World Haptics Conference,* 22–24.

Mulavara, A. P., Cohen, H. S., & Bloomberg, J. J. (2009). Critical features of training that facilitate adaptive generalization of over ground locomotion. *Gait Posture, 29*(2), 242–248.

Norman, D. A. (1988). *The psychology of everyday things.* New York: Basic Books.

Park, O. C., & Hopkins, R. (1992). Instructional conditions for using dynamic visual displays: A review. *Instructional Science, 21*(6), 427–449.

Patton, J. L., Stoykov, M. E., Kovic, M., & Mussa-Ivaldi, F. A. (2006). Evaluation of robotic training forces that either enhance or reduce error in chronic hemiparetic stroke survivors. *Experimental Brain Research, 168*(3), 368–383.

Riccio, G. E. (1995). Coordination of postural control and vehicular control: Implications for multimodal perception and simulation of self-motion. *Local Applications of the Ecological Approach to Human Machine Systems, 2,* 122–181.

Rosser, J. C., Jr., Lynch, P. J., Cuddihy, L., Gentile, D. A., Klonsky, J., & Merrell, R. (2007). The impact of video games on training surgeons in the 21st century. *Archives of Surgery, 142*(2), 181.

Ruffaldi, E., Filippeschi, A., Frisoli, A., Sandoval, O., Avizzano, C. A., & Bergamasco, M. (2009). Vibrotactile perception assessment for a rowing training system. *Proceedings of the Third IEEE Joint Conference on Haptics, World Haptics.* doi: http://doi.ieeecomputersociety.org/10.1109/WHC.2009.4810849.

Ruffaldi, E., Filippeschi, A., Frisoli, A., Avizzano, C. A., Bardy, B., Gopher, D., et al. (2009). SPRINT: A training system for skills transfer in rowing. In T. Gutierrez & E. Sanchez (Eds.), *SKILLS09 International Conference on Multimodal Interfaces for Skills Transfer.*

Ruffaldi, E., Filippeschi, A., Avizzano, C. A., & Bergamasco, M. (2010). Skill modeling and feedback design for training rowing with virtual environments. *Proceedings of the 3rd Conference on Human Factors and Ergonomics,* 832–841.

Schmidt, R., & Lee, T. (2005). *Motor control and learning: A behavioral emphasis* (4th ed.) Champaign, IL: Human Kinetics Publishers.

Shepherd, A. (1985). Hierarchical task analysis and training decisions. *Innovations in Education and Teaching International, 22*(2), 162–176.

Slater, M. (2009). Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society of London (B), 364*(1535), 3549–3557.

Slater, M., Linakis, V., Usoh, M., & Kooper, R. (1996). Immersion, presence and performance in virtual environments: An experiment with tri-dimensional chess. *ACM Virtual Reality Software and Technology (VRST),* 163–172.

Slater, M., Perez-Marcos, D., Ehrsson, H. H., & Sanchez-Vives, M. V. (2008). Towards a digital body: The virtual arm illusion. *Frontiers in Human Neuroscience, 2.*

Stanney, K. M., Mourant, R. R., & Kennedy, R. S. (1998). Human factors issues in virtual environments: A review of the literature. *Presence: Teleoperators and Virtual Environments, 7,* 327–351.

Stoffregen, T. A., & Bardy, B. G. (2001). On specification and the senses. *Behavioral and Brain Sciences, 24,* 195–261.

Stoffregen, T. A., Bardy, B. G., Smart, L. J., & Pagulayan, R. (2002). On the nature and evaluation of fidelity in virtual environments. *Handbook of virtual environments: Design, implementation, and applications* (p. 111). Boca Raton, FL: CRC Press.

Vander Linden, D. W., Cauraugh, J. H., & Greene, T. A. (1993). The effect of frequency of kinetic feedback on learning an isometric force production task in nondisabled subjects. *Physical Therapy, 73*(2), 79.

Varlet, M., Marin, L., Lagarde, J., & Bardy, B. G. (2010). Social postural coordination. *Journal of Experimental Psychology: Human Perception and Performance (*in press).

Vignais, N., Bideau, B., Craig, C., Brault, S., Multon, F., Delamarche, P., et al. (2009). Does the level of graphical detail of a virtual handball thrower influence a goalkeeper's motor response? *Journal of Sports Science and Medicine, 8,* 501–508.

Virsu, V., Oksanen-Hennah, H., Vedenpaa, A., Jaatinen, P., & Lahti-Nuuttila, P. (2008). Simultaneity learning in vision, audition, tactile sense and their cross-modal combinations. *Experimental Brain Research, 186*(4), 525–537.

von Zitzewitz, J., Wolf, P., Novakovic, V., Wellner, M., Rauter, G., Brunschweiler, A., et al. (2008). Real-time rowing simulator with multimodal feedback. *Sports Technology, 1*(6), 257–266.

Warren, W. H. (1984). Perceiving affordances: Visual guidance of stair climbing. *Journal of Experimental Psychology: Human Perception and Performance, 10*(5), 683–703.

Wickens, C. D., & Hollands, J. G. (1999). *Engineering psychology and human performance.* Upper Saddle River, NJ: Prentice Hall.

Williams, A. M., & Hodges, N. J. (2004). *Skill acquisition in sport: Research, theory and practice*. London: Routledge.

Winstein, C. J., & Schmidt, R. A. (1990). Reduced frequency of knowledge of results enhances motor skill learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16*(4), 677–691.

Winstein, C. J., Pohl, P. S., Cardinale, C., Green, A., Scholtz, L., & Waters, C. S. (1996). Learning a partial-weight-bearing skill: Effectiveness of two forms of feedback. *Physical Therapy, 76*(9), 985–993.

Wulf, G., & Schmidt, R. A. (1997). Variability of practice and implicit motor learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23*(4), 987–1006.

Wulf, G., & Shea, C. H. (1999). Enhancing motor learning through external-focus instructions and feedback. *Human Movement Science, 18*, 553–571.

Wulf, G., & Shea, C. H. (2002). Principles derived from the study of simple skills do not generalize to complex skill learning. *Psychonomic Bulletin & Review, 9*(2), 185–211.

Yao, W. X., DeSola, W., & Bi, Z. C. (2009). Variable practice versus constant practice in the acquisition of wheelchair propulsive speeds. *Perceptual and Motor Skills, 109*(1), 133–139.

Zanone, P. G., & Kelso, J. A. S. (1992). Evolution of behavioral attractors with learning: Nonequilibrium phase transitions. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 403–421.