Investigating the use of Co-Embodiment and Kinesthetic co-manipulation for improving technical Skill learning in Virtual Reality

1. Context

Traditionally, learners are trained based on the mentorship model when learning a technical gesture: the expert ensures the transfer of skills to the novice through collaborative actions and demonstrations. During the initial stages of learning, the expert's instructions and corrections contribute to improving learning [4]. To avoid risky situations during training (especially in the medical field), the utility of immersive virtual environments (IVE) has been demonstrated [6]. However, in current IVEs, learners often work independently and thus lack expert guidance and feedback. To stay within the mentorship model, it is necessary to use Collaborative Virtual Environments (CVE) where experts can also be present in the IVE or have communication modalities to interact with the learner.

2. Challenges

Within IVE, partners can communicate using several modalities [14]. It has been demonstrated that combining different modalities can improve communication and collaboration within a CVE [16]. Studies show, in particular, that guidance using a combination of visual and haptic modalities is best suited to improve learners' performance [16] and reduce mental load [17]. However, the effect of VR and multimodal approaches on learning, particularly for acquiring technical skills, requires further research to understand better the underlying skill transfer mechanisms [11]. Notably, overly frequent corrections or obvious guidance can hinder learning and, above all, long-term retention of the technical skill [1] (this difference between expected and actual results is now known as the Guidance Hypothesis). The central nervous system (CNS) relies on the coding and storage of control loops between proprioceptive and visual inputs and motor outputs to perform dynamic tasks. To update this control loop and master the required skill, a strong sense of agency (SoA) toward the movement is required. SoA is the subjective feeling of initiating and controlling an action, which arises when the predicted outcome is perceived as consistent with the actual outcome. In the presence of guidance, the SoA is weak; the CNS cannot code and retain the loop as it would during active practice [2]. Moreover, the learner will make fewer errors by being constrained to an optimal trajectory, but these errors will stimulate learning [3]. Finding a guidance method that accelerates learning while preserving long-term skill retention is necessary [7].

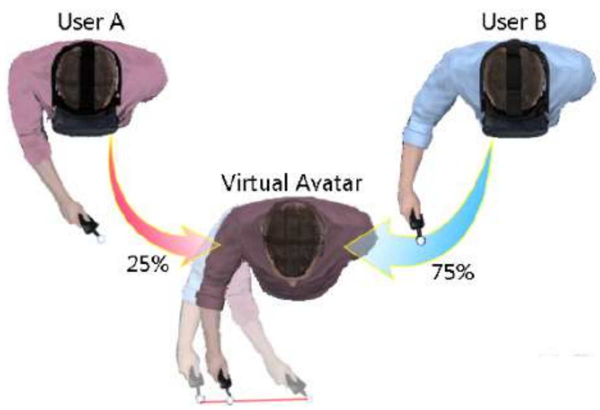

Figure 1. Illustration of the co-embodiment technique where the avatar's movements are a combination of 25% of User A's movements and 75% of User B's movements.

3. Approach and Originality

Going beyond common interactions in CVEs, researchers have recently explored the concept of virtual co-embodiment [9], where two users can be immersed in a virtual environment in first-person view and can have complementary levels of control (total, partial, or none) over a shared avatar (see Figure 1). With this method, users, despite a good understanding of their level of control, overestimate their sense of agency (SoA). It has been shown that learning while accompanied by an expert using co-embodiment improves the efficiency of learning technical skills and increases their short-term retention compared to learning alone or passively following an expert's gestures [13]. We propose to use co-embodiment and explore the benefits of this technique for the long-term retention of technical skills. Co-embodiment is a **visual** interaction technique between the expert and the learner. We have seen that multiplying interaction modalities is beneficial for learning and is also helpful in reinforcing the SoA. Indeed, if the information stimulating different sensory modalities is consistent, the SoA is reinforced. A recently defended hypothesis is that if sensory cues are reliable, SoA can emerge even for unintended actions [8]. We, therefore, want to extend the co-embodiment paradigm by adding a kinesthetic channel between the expert and the learner. In fact, haptically coupled human-human dyads make faster group decisions and can implicitly share confidence [10]. They can also handle asymmetric information about a co-manipulative task and solve conflicts using only the kinesthetic channel [12]. It also allows better learning and performance in tracking tasks, even in conflicts [5].

4. Objectives and methods

The first objective of this research is to investigate the benefit of co-embodiment for long-term retention of technical skills. We also want to compare the effectiveness of skill transfer between an expert and a novice using the co-embodiment alone, a kinesthetic link alone, and a combination of these two methods, especially the effect on long-term retention. This project's broader objective is to understand better the links between the agency and the joint agency in the long-term retention of technical skills. A strong SoA is often associated with good skill retention; however, a characterization of the agency role in skill learning is still lacking [15]. Moreover, within the mentorship model, we will also investigate the effect of joint agency on learning. A final application would be to use our result to dynamically adjust the levels of controls during a co-embodiment and kinesthetic co-manipulation task to enhance the learning of technical skills. At the IBISC Laboratory (Université d'Evry), we already have a learning platform with kinesthetic coupling between users (see Figure 2). This can be used as a base to conduct two experimental studies. The first one aims to study the retention of technical skills with different interaction methods. The second one aims to investigate the benefits of dynamic levels of control. We aim to measure the SoA using subjective measures such as questionnaires. We also would like to use objective measures such as temporal binding and EEG. Finally, we will assess the learning and retention of skills using objective measurements (time, accuracy).

5. Project Organization

5.1. Timeline and partnership

The requested funding is for an 18-month post-doc position. The first six months will be dedicated to improving the co-embodiment platform and kinesthetic coupling and enriching our state-of-the-art on SoA and Skills Learning. Then, we will conduct our first user experiment and analyze the result during the following three months. We will dedicate the subsequent six months to preparing and conducting the second experiment and the final three months to analysis and publication. The project will be carried out in collaboration with Amine Chellali (IRA2 team, IBISC) and Ludovic Saint-Bauzel (IRIS team, ISIR). Flavien will have an office at both sites. The IRA2 team will manage administrative supervision. The IRIS team will contribute its expertise in physical interactions, joint actions, and the sense of agency. The IRA2 team will provide expertise in collaborative virtual environments, technical skill learning, and the sense of embodiment.

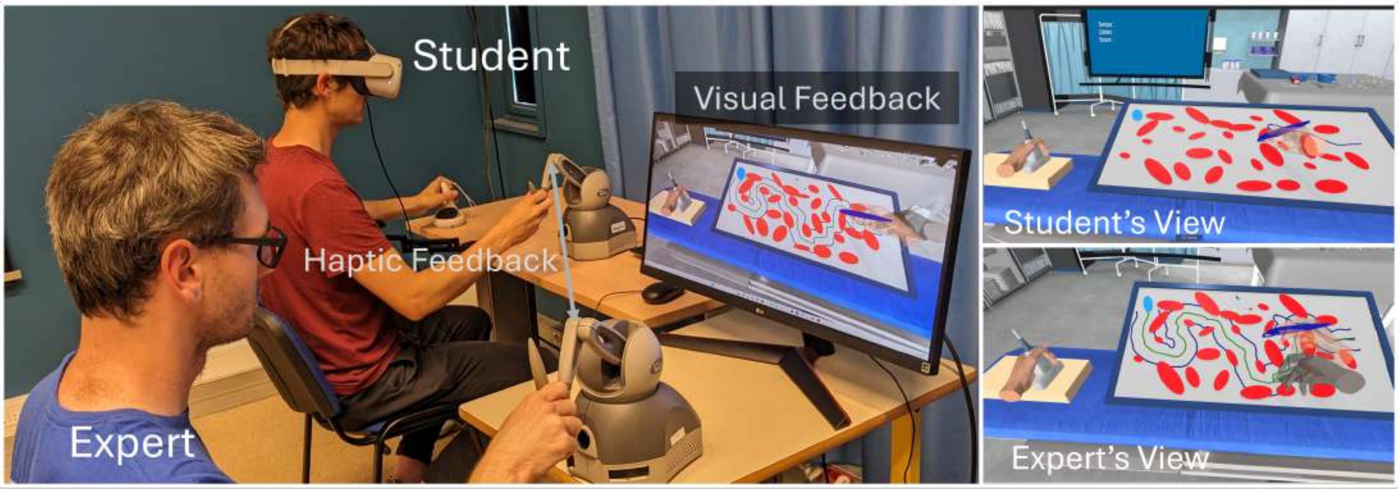

Figure 2. Illustration of the learning platform. Here, an expert guides a learner in virtual reality by monitoring their progress on a screen. Corrections are provided visually and haptically through kinesthetic interfaces.

5.2. Adequacy with the objectives of PEPR eNSEMBLE and PC1

This project aligns perfectly with the scientific challenges of PC1 CATS within the PEPR eNSEMBLE. Indeed, it addresses the three dimensions of the collaboration space by enabling collaboration between a learner and an expert, each performing complementary tasks within the shared environment while supporting multisensory interpersonal interactions between them. The project will particularly contribute to WPs 1.1, 1.2, and 1.3 of Axis 1 by exploring modalities, techniques, and devices for realistic collaborative and multi-sensory interactions, as well as to WP 2.2 of Axis 2 by investigating the sense of co-embodiment through multi-sensory avatars in human collaboration scenarios. Moreover, we want to highlight that co-manipulation can occur in heterogeneous space (the learner is in VR while the mentor is in front of a PC screen, remote, in AR, or only connected with a haptic interface). We see common interest with at least 3 PhD theses of the PC1. The first thesis (Support grants) is supervised by Amine Chellali (**Study of interpersonal haptic interactions between virtual avatars**), the second one (fully funded) is supervised by Ludovic Saint-Bauzel (**Learning through kinesthetic relationship and brain synchronization**). A third one (**Joint Actions in a Collaborative Digital Environments: co-gestures and a Sense of Agency**) focuses on the sense of agency in the context of joint actions among multiple individuals (fully funded). Finally, within the framework of the postdoc, it will be possible to organize workshops on agency, co-agency, and haptic collaboration in hybrid environments.

■ References

[1] R. A. Schmidt and R. A. Bjork, “New conceptualizations of practice: Common principles in three paradigms suggest new concepts for training”, *Psychological science*, vol. 3, no. 4, pp. 207–218, 1992.

[2] R. Shadmehr and F. A. Mussa-Ivaldi, “Adaptive representation of dynamics during learning of a motor task”, *Journal of neuroscience*, vol. 14, no. 5, pp. 3208–3224, 1994.

[3] K. A. Thoroughman and R. Shadmehr, “Learning of action through adaptive combination of motor primitives”, *Nature*, vol. 407, no. 6805, pp. 742–747, 2000.

[4] M. J. Barrington, D. M. Wong, B. Slater, J. J. Ivanusic, and M. Ovens, “Ultrasound-guided regional anesthesia: How much practice do novices require before achieving competency in ultrasound needle visualization using a cadaver model”, *Regional Anesthesia & Pain Medicine*, vol. 37, no. 3, pp. 334–339, 2012. DOI: https://doi.org/10.1097/AAP.0b013e3182475fba.

[5] G. Ganesh, A. Takagi, R. Osu, T. Yoshioka, M. Kawato, and E. Burdet, “Two is better than one: Physical interactions improve motor performance in humans”, *Scientific reports*, vol. 4, no. 1, p. 3824, 2014.

[6] A. Chellali, W. Ahn, G. Sankaranarayanan, *et al.*, “Preliminary evaluation of the pattern cutting and the ligating loop virtual laparoscopic trainers”, *Surgical endoscopy*, vol. 29, pp. 815–821, 2015.

[7] N. Braun, S. Debener, N. Spychala, *et al.*, "The senses of agency and ownership: A review", *Frontiers in psychology*, vol. 9, p. 535, 2018.

[8] R. Legaspi and T. Toyoizumi, "A bayesian psychophysics model of sense of agency", *Nature communications*, vol. 10, no. 1, p. 4250, 2019.

[9] R. Fribourg, N. Ogawa, L. Hoyet, *et al.*, "Virtual co-embodiment: Evaluation of the sense of agency while sharing the control of a virtual body among two individuals", *IEEE Transactions on Visualization and Computer graphics*, vol. 27, no. 10, pp. 4023–4038, 2020.

[10] G. Pezzulo, L. Roche, and L. Saint-Bauzel, "Haptic communication optimises joint decisions and affords implicit confidence sharing", *Scientific Reports*, vol. 11, no. 1, p. 1051, 2021.

[11] D. Martin, S. Malpica, D. Gutierrez, B. Masia, and A. Serrano, "Multimodality in vr: A survey", *ACM Computing Surveys (CSUR)*, vol. 54, no. 10s, pp. 1–36, 2022.

[12] L. Roche and L. Saint-Bauzel, "Study of kinesthetic negotiation ability in lightweight comanipulative decision-making tasks: Design and study of a virtual partner based on human-human interaction observation", *ACM Transactions on Human-Robot Interaction (THRI)*, vol. 11, no. 2, pp. 1–23, 2022.

[13] D. Kodama, T. Mizuho, Y. Hatada, T. Narumi, and M. Hirose, "Effects of collaborative training using virtual co-embodiment on motor skill learning", *IEEE Transactions on Visualization and Computer Graphics*, vol. 29, no. 5, pp. 2304–2314, 2023.

[14] C. Simon, M. Boukli-Hacene, S. Otmane, and A. Chellali, "Study of communication modalities to support teaching tool manipulation skills in a shared immersive environment", *Computers & Graphics*, vol. 117, pp. 31–41, 2023.

[15] V. Cesari, S. D'Aversa, A. Piarulli, F. Melfi, A. Gemignani, and D. Menicucci, "Sense of agency and skills learning in virtual-mediated environment: A systematic review", *Brain Sciences*, vol. 14, no. 4, p. 350, 2024.

[16] C. Simon, M. Boukli-Hacene, F. Lebrun, S. Otmane, and A. Chellali, "Impact of multimodal instructions for tool manipulation skills on performance and user experience in an immersive environment", in *2024 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*, IEEE, 2024, pp. 670–680.

[17] F. Lebrun, C. Simon, A. Boukezzi, S. Otmane, and A. Chellali, "Mentor-guided learning in immersive virtual environments: The impact of visual and haptic feedback on skill acquisition", in *32nd IEEE Conference On Virtual Reality And 3d User Interfaces (VR 2024)*, 2025.