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Hiding Assistive Robots During Training in Immersive VR Does Not Affect Users' Motivation, Presence, Embodiment, Performance, Nor Visual Attention

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***Abstract*— Combining immersive virtual reality (VR) using head-mounted displays (HMDs) with assisting robotic devices might be a promising procedure to enhance neurorehabilitation. However, it is still an open question how immersive virtual environments (VE) should be designed when interacting with rehabilitation robots. In conventional training, the robot is usually not visually represented in the VE, resulting in a visuo-haptic sensory conflict between what users see and feel. This study aimed to investigate how motivation, embodiment, and presence are affected by this visuo-haptic sensory conflict. Using an HMD and a rehabilitation robot, 28 healthy participants performed a path-tracing task, while the robot was either visually reproduced in the VE or not and while the robot either assisted the movements or not. Participants' performance and visual attention were measured during the tasks, and after each visibility/assistance condition, they reported their motivation, presence, and embodiment with questionnaires. We found that, independently of the assistance, the robot visibility did not affect participants' motivation, presence, embodiment, nor task performance. We only found a greater effort/importance reported when the robot was visible. The visual attention was also slightly affected by the robot's visibility. Importantly, we found that the robotic assistance hampered presence and embodiment, but improved motivation. Our results indicate no disadvantage of not reproducing robotic devices in VEs when using HMDs. However, caution must be put when developing assisting controllers, as they might hamper users' affect.**

***Index Terms*— Attention, embodiment, gaze, head-mounted display, motivation, presence, rehabilitation, robot, upper-limb, virtual reality.**

I. Introduction

MOTOR training requires a high number of movement repetitions to promote motor learning and functional recovery [1]. An increasing number of rehabilitation robots emerged in the last two decades to support therapists during this high-intensity training by assisting patients in their movements [2]. However, high-intensity training (i.e., high number of movement repetitions and frequency of training) can only be achieved when patients remain motivated and attentive on the task during the long rehabilitation interventions. Indeed, patients' motivation and attention have been described as key aspects to enhance neurorehabilitation [3]. Motivation has been shown to have both indirect (e.g., by increasing the amount of movement repetitions) and direct (e.g., improving memory consolidation) effects on learning [4]. The *OPTIMAL* theory states that motivation and attention have a positive effect on motor learning, possibly due to the release of dopamine [5].

To enhance patients' **motivation**, Virtual Reality (VR) is employed, e.g., to render virtual environments where meaningful goal-directed movements are trained [6] or through the addition of game mechanisms [7]. Along with motivation, VR has a positive effect on several – interrelated – affective constructs, such as the experienced level of immersion and presence in the virtual environment (VE) [8]. **Immersion** refers to the technical capability of the VR system (hardware and software) to refocus the user's sensation from being in the real to a virtual world [9]. **Presence** refers to the subjective feeling of being in the VE [10]. In immersive VR – e.g., with head-mounted displays (HMD) – avatars can be employed to represent the user's body. Users may then embody this avatar and experience the feeling of **body ownership** over the virtual body. Body ownership is defined as the cognition that a body and its parts belong to oneself [11]. Importantly, a high experienced level of body ownership over an avatar in immersive VR has been linked to better motor performance [12], [13]. In a recent study, we showed that visualizing three-dimensional arm reaching movements using an avatar perceived from a first-person perspective with an immersive VR HMD facilitated motor performance [14] and enhanced users' motivation and body ownership over the avatar [15], compared to a less immersive computer screen.

Finally, an important benefit of the immersion achieved with HMDs [16] is that the users are detached from the real world, potentially enhancing their **attention** on the task [17] and limiting real-world distractors. This increased attention may be of great advantage, especially in the training of brain-injured patients, as attentional deficits are one of the

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most prominent neuropsychological disorders after stroke [17]. The immersion of VR using HMD and the associated detachment of the participants from the physical world allows to create new immersive VEs that differ from the real world, e.g., in robot-based rehabilitation settings, the robotic device is not visible by default.

Together, immersive VR may crucially influence users' affect such as motivation, sense of presence, embodiment, and attention during VR-based robotic neurorehabilitation. Exploiting these interrelated user affects in a holistic way during VR-based motor training might further boost motor learning and neurorehabilitation.

Although increasing effort has been put into understanding the potential benefits of immersive VR on users' affect and motor performance [12], [14], [18]–[20], previous research contained interactions with the VE that differ from those during robot-assisted VR-based therapy. In the cited research, participants interacted with the VE using controllers instead of assisting robotic devices. Thus, participants did not feel any external assisting forces during training, which might also have an effect on their affect, as shown in non-immersive robotic-assisted training [21]–[23]. Further, in current immersive VR the robot is not visualized in the VE. The provision of assisting forces to participants while interacting with immersive VEs where the robot is not visualized raises a new research question, which in this paper we aim to answer: If the robot is not visually represented in the VE, how would the sensory mismatch of feeling the assisting forces whose origin cannot be visually located impact users' affect?

Preliminary studies found contradictory effects of such a sensory mismatch on the users' affect. First, users' motivation could be increased by being naive to the assistance source, as users might believe that they are more skilled than they really are. This is supported by a recent study that showed that displaying participants' performance as being better than in reality increases brain-injured patients' use of the paretic limb after training [24]. The authors attributed this effect to a potential increase in patients' expected competence. A more recent study found that healthy participants tend to attribute a force as their own if it assists towards their desired outcome [25]. Therefore, high motivation could be expected if participants, who are immersed in VR, perceive themselves as performing well thanks to an assisting force whose source (the robot) is invisible in the VE. In contrast, when the robot is visible, the opposite effect could be expected: seeing the robot might remind them that their good performance is due to the robotic assistance and, therefore, reduce their motivation. Second, not being able to see the robot in immersive VR might create a visuo-haptic conflict that could hinder the sense of presence and hamper motor performance. Although no previous research has evaluated the effect of this specific sensory mismatch on motor training, research investigating other types of sensory mismatches suggest that a spatial shift between haptic and visual information leads to a decrease in presence, but a delay in vision does not [26]. Importantly, the incongruency of visuo-haptic sensory information seems to hinder motor performance, specially in highly embodied VR [12]. Finally, we can expect that the visuo-haptic sensory mismatch might hamper the body ownership. Conflicting sensory information might impair body ownership, as it is assumed to be a bottom-up process integrating multiple sensory information [11]. In fact, in several experiments, body ownership is modulated by inducing sensory incongruency [12], [13].

The selected robotic training strategies might also directly impact the previously mentioned user affects. In robotic rehabilitation, different training strategies modulating the level and type of provided assistance have been developed, which may differently affect users' motivation, attention, and presence [27], [28]. For example, healthy adults felt more competent and satisfied in a golf-putting task when assisted by a robot versus when the robot augmented their error [21]. However, excessive assistance might also encourage patients to rely on the assistance and reduce their attention and effort [29], [30]. Robotic assistance might also lower the experienced embodiment over an avatar if it reduces the sense of agency – i.e., the experience that oneself is initiating and controlling an external event through one's own actions [31], [32]. In some cases, the assistance might even be felt as a disturbance rather than as guidance [33], and thus, act as a distractor and limit the feeling of presence in the VE.

This study aims to investigate how users' affect – namely, motivation, presence, embodiment, and visual attention – of healthy participants are influenced by visualizing or not the upper-limb rehabilitation robot they are attached to and that assists them or not during a tracing task in VR. We developed an immersive VR system with an HMD and a first-person perspective avatar plus a realistic visual representation of the assistive robot. All participants performed the task in the four different conditions in a within-subject design (*Invisible/Visible robot* x *With/Without assistance*), reporting each time their affective experience using questionnaires. We hypothesized that: 1) when participants are assisted, the presence and embodiment – especially the agency subscale – would decrease if the robot is not visible; and 2) when participants are not assisted, the motivation – especially the perceived competence – would increase when the robot is not visible. To further investigate differences in visual attention – reliably reflected in the gaze behavior [34], [35] – between conditions, we used an HMD-embedded eye-tracker.

II. Materials and Methods

A. Experimental Setup

1) Robot: The commercially available upper-limb rehabilitation end-effector robot Burt® (Barrett Technology, LLC, USA) was used in the experiment (Fig. 1). Burt® has three actuated degrees of freedom (DoF), which allow translation of the users' forearm in Cartesian space. The controller to provide assistance was implemented with the *BurtSharp* library in C# and run on the Burt console operating under Linux (Ubuntu 16.04.7 LTS) at 500 Hz. A second computer (VR-computer) executed the VR application. The *BurtSharp* library was used to also communicate the robot's state to the VR-computer through the user datagram protocol (UDP) at approx. 500 Hz.

2) Virtual Reality: The VR system included an HTC Vive Pro Eye with two SteamVR™ Base Station 2.0 and two HTC Vive trackers (2018) (HTC Vive, HTC, Taiwan & Valve, USA;

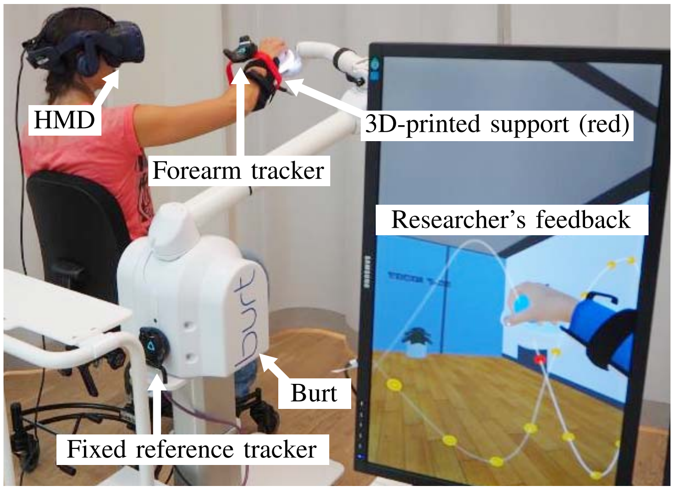

Fig. 1. Experimental setup with the Burt® robot (Barrett Technology, LLC, USA), the HTC Vive Pro Eye HMD and two trackers (HTC Vive, HTC, Taiwan & Valve, USA), the 3D-printed forearm tracker support (in red), and the screen for the researcher's visual feedback.

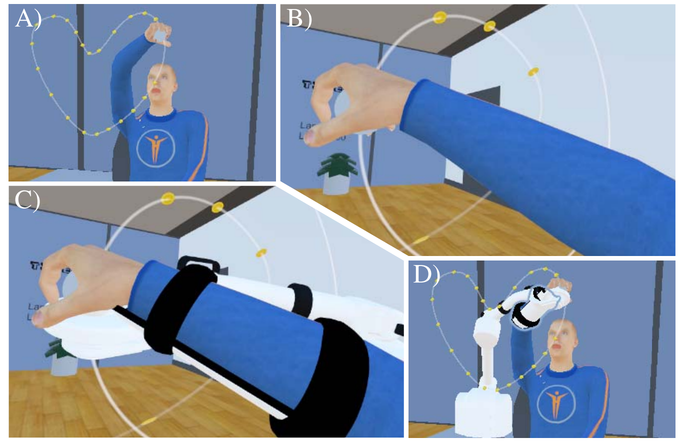

Fig. 2. Virtual environment. A) & D) Third-person perspective showing the avatar and a whole path – This view was not presented to the participants. B) & C) Participants' first-person perspective during the task. A) & B) *Invisible* conditions showing some office supplies, the path, coins, and the avatar. C) & D) *Visible* conditions showing (in addition) the robot including the forearm cuff.

Fig. 1). The first tracker, placed at a fixed reference location on the static robot base, allowed to know the transformation between the robot's coordinate system and the VR tracking one. Participants were attached to the robot end-effector through a forearm cuff with one (unsensorized) degree of freedom. Thus, the second tracker was placed on the robot forearm cuff, using a custom-made 3D printed structure, to retrieve the forearm orientation and animate the avatar properly.

To develop the VR task (see section II-B), Unity version 2019.3.3f1 was used. The SteamVR plugin v2.0 and the "Valve.VR" SDK (Valve Corporation, USA) were employed to interface the HTC Vive Pro and the HTC Vive trackers (2018). Finally, the SRanipal SDK v2 was used to interface the build-in eye tracker at the HMD in an asynchronous manner (independently of Unity's refresh rate). The VR-computer had an Intel Core i7-8700K CPU (Intel Corporation, USA), an NVIDIA GeForce GTX 1080 Ti GPU (NVIDIA Corporation, USA), 32 GB of DDR3 RAM, and operated under Windows 10 Home 64 bits (Microsoft Corporation, USA).

B. Virtual Environment and Tracing Task

The VE was composed of a basic reproduction of our laboratory (with basic office supplies), an avatar, a user interface, coins, and paths (Fig. 2). Participants were immersed in the VE from the avatar's first-person perspective (Fig. 2, B & C). The avatar's head and right arm were animated using the position and orientation of, respectively, the HMD and the forearm tracker. The avatar's appearance was the same for all participants.

Participants were instructed to follow virtual paths presented in front of them as fast and precisely as possible with their right hand. While following the path, participants were requested to collect all coins on the path by touching them with a sphere held in the avatar's hand, which resembled the real sphere participants held on the robot end-effector. The paths were defined by composite cubic Bezier curves and scaled to the participant's workspace (obtained in an initial calibration phase, see section II-E). To indicate that a coin was collected, the coin would disappear and a sound (similar to the iconic "Mario" coin sound; Nintendo, Japan) was played via the HTC Vive's integrated headphones.

There were a total of seven different paths and, on each path, participants had to trace two laps in a row – i.e., collect two times the coins that reappeared on the second lap as soon as the last coin of the first lap was collected. If the second lap was completed faster than the first one, an applause sound was played. The order of the paths was randomized across participants and conditions. The user interface informed the participants about the time they took to complete the current and previous laps. This user interface was located in the virtual environment, in front of the participant, far (≈ 7 m) behind the task workspace.

C. Experimental Conditions

1) Robot Visibility: The robot **visibility** in the VE changed across conditions. During the *Visible* conditions (Fig. 2, C & D), the VE contained a reproduction of the robot, including the forearm cuff. The 3D model was provided by Barrett Technology and the forearm cuff modeled in Blender (Blender Foundation, community). The virtual robotic arm links were animated using the angles of the real robot joints obtained with the *BurtSharp* library and occupied the same space as the real ones. During the *Invisible* conditions (Fig. 2, A & B), the virtual robot and the forearm cuff were not visible.

2) Robotic Assistance: The **assistance** that the robot provided to the participants during the task also changed between conditions. During the *Without assistance* conditions, the robot did not apply forces to assist the participants, but followed participants self-selected movements. We employed the transparent mode controller already implemented in Burt®. During the *With assistance* conditions, participants were physically assisted by the robot to perform the task. We implemented a path-controller that provided assisting forces to move the robot end-effector towards its closest point on the path. We selected a path controller as the assistance strategy as it is well-known and commonly used in robotic rehabilitation [27], [36], [37].

In order to calculate the closest point on the path, the path was first discretized in 400 points (100 per Bezier curve). Then, the point on the path closest to the current end-effector position was retrieved. As some of our paths could cross several times through the same points, the set of potential closest points on the path was reduced to the previous closest point and its two direct neighbours (forward and backward). The assisting force, F_{robot}, was then computed as [36], [37]:

$$e = \| P_{actual} - P_{closest\,Point\,Path} \|$$
$$F_{robot} = -ke - b\frac{de}{dt}, \quad (1)$$

where k is the stiffness, set to 250.0 N/m, and b is the damping coefficient, set to 2.0 Ns/m. The position error e is the calculated distance between the robot end-effector position, P_{actual}, and the closest point on the path, $P_{closest\,Point\,Path}$, while $\frac{de}{dt}$ is its derivative. Only in the assistance condition, as soon as a path appeared, the robot guided the participant's hand to the path start point with a proportional-derivative (PD) controller.

D. Participants

Twenty-eight healthy participants, aged from 21 to 64 years (34.35 ± 13.32), provided written informed consent to participate in the study. All participants reported normal or corrected-to-normal vision. All participants except one reported to be right-handed. The recruitment of participants was performed within the University of Bern via word-of-mouth. The study was approved by the local Ethics Committee (ref: 2018-01179) and conducted in compliance with the Declaration of Helsinki.

E. Experimental Protocol

At the beginning of the experiment, participants received written instructions about the task to be performed. They sat on a chair and their right forearm was attached to the robot forearm cuff with hook-and-loop fasteners straps. Before the experiment start, participants went through a workspace calibration process. They were asked to extend their right arm horizontally as much as possible, and then to bring their right hand as close as possible to their sternum. The maximum and minimum distances were used to scale the task workspace.

Each participant performed the task (i.e., trace seven paths two times) in four different conditions in a within-subject design (*Invisible/Visible robot* x *With/Without assistance*). The order of the four conditions was such that the two conditions with the same assistance method (*With* or *Without*) were kept consecutive. The order of the assistance and visibility conditions was balanced across participants.

After each condition, participants removed the HMD and were asked to fill in a battery of questionnaires (see subsection II-F.1). The experiment lasted around one hour, with an average of 179 ± 82 seconds spent in the VR for each condition.

F. Data Processing

1) Questionnaires: After the task, for each condition, participants were requested to fill in the questionnaires using REDCap electronic data capture tools [38], hosted at the University of Bern.

To assess their **motivation**, participants answered 27 questions selected from the well-established Intrinsic Motivation Inventory (IMI) [39] using a seven-point Likert scale; 1 indicated "not at all true" and 7 indicated "very true". Five IMI subscales were selected for their relevance in our current study: *Interest/Enjoyment*, *Perceived Competence*, *Effort/Importance*, *Pressure/Tension*, and *Relatedness*. We only included half of the original items from the *Relatedness* subscale and replaced the original term "*person*" by "*robot*" to evaluate the *Trust* that participants felt in their interaction with the robot.

To assess their sense of **presence**, participants responded to 10 questions selected from the well-established Presence questionnaire [40] using a seven-point Likert scale; 1 indicated "not" and 7 indicated "very". From the original 32 questions, only the ones from the *Distraction*, *Realism*, and *Involvement/Control* subscales were selected and adapted to our application (i.e., changing "*control devices*" and "*control mechanism*" to "*robot*").

To assess their subjective feeling of **embodiment** towards the avatar, participants responded to six questions selected and adapted from questionnaires frequently used in rubber hand illusions studies [41], [42] using a seven-point Likert scale; -3 indicated "strongly disagree" and 3 indicated "strongly agree". From the three components of embodiment, only questions from the *Body ownership* and *Agency* components were selected, as we did not expect changes in *(Self-)location*.

For each questionnaire, the questions' scores were reversed if needed and averaged into a single value per subscale. At the end of the experiment, participants answered an extra question to report whether they noticed or not the difference in the robot's visibility between conditions. The possible answers were "*No; I did not realize it*", "*Yes; I realized the difference in the first two tasks*", "*Yes; I realized the difference in the last two tasks*", and "*Yes; I realized it both times*".

2) Task Performance: The three robot joint angles were retrieved from the UDP communication between the Burt console and VR-computer and used to calculate the robot end-effector position in Cartesian coordinates. The data were then cut into laps. Each lap start and end were defined as the time when the virtual end-effector touched, respectively, the first and last coins on the path.

The task performance was evaluated using the average **path error**. This error was computed for each lap as the mean squared error between the actual end-effector position and the closest point on the path. The path's closest points were computed as in our path-controller implementation (section II-B), but with the spline discretized in 3000 points, equally distributed within each segment. We then averaged the error for each path, and then all paths' mean path errors were averaged into a single value for each condition, resulting in 28 x 4 values. We also evaluated the average **lap completion time**, computed for each lap and averaged with the same two-steps process as the path error. As the end-effector (real and virtual) had a radius of 3.1 cm, the lap start was adapted for these two metrics as the time at which the end-effector was the closest to the path's first point. This post-processing was performed in Python version 3.7.9 and the packages pandas 1.1.3 and numpy 1.19.2.

3) Visual Attention: To investigate whether the visual attention was affected by the *Visibility* of the robot or the robotic *Assistance*, we recorded the gaze behavior (i.e., eye tracker data) during task execution at 120 Hz. We then computed the **fixation time ratio** that participants spent looking at relevant virtual elements of the VE in a post-processing step. We were specially interested on the time participants spent looking at the: *Path*, *End-effector*, *Avatar*, *Robot*, and *Others*.

To calculate fixation time ratios, we first computed the gaze's endpoints for each recorded frame using Unity. The gaze's endpoints were computed by casting a ray from the recreated gaze origin point (eyes' location) and detecting the ray's first collision with one of the virtual element of interest (using colliders). If no colliders were hit, the gaze endpoint was categorized as *Others*. To tolerate a worst eye tracker imprecision of 6.21° [43], we modified the collider dimensions proportionally to their average distance to the eyes. For the *Avatar* category, no collider for the hand was implemented and no tolerance was used for the other arm colliders, as this would have occluded other categories (e.g., the *Path*). If the first collider hit was the *Path*, the ray was prolongated until it reached the path's plane. If another collider was hit before the plane, the other category was selected. The robot was also animated (although not visible) during the *Invisible* conditions, so the *Robot* fixation time ratio computed during the *Invisible* conditions reflects the time participants looked at the space that would have been occupied by the robot if it would have been visible. For each lap, the time participants spent looking at each category was accumulated and normalized by the lap completion time to obtain fixation time ratios.

4) "Unnatural" Controller Behavior: While running the experiment, we observed that several participants tried to cut the paths in sharp curves. This behavior led to the closest point estimation being "stuck" on the first part of the curve, while participants wanted to move the end-effector closer to the second part. This produced an "unnatural" behavior in the path controller, as the provided force was pushing participants backwards to bring them back to the path. This could have been perceived by the participants as a disturbance, rather than assistance. To prevent this unnatural behavior to affect the task performance and visual attention analyses, we performed a visual inspection of the end-effector positions and their corresponding closest points (computed with our algorithm) during post-processing. All laps identified as having some closest points being on the "undesired" side of a sharp angle (16% of the total laps) were therefore removed from the task performance and visual attention analyses.

Due to issues in the recording script when the application was manually closed, 24 laps were further discarded. To achieve a comparable number of averaged metrics within each participant, if both laps of the same path were to be excluded, the corresponding laps were removed from each condition for the same participant. In total, 1281 laps were included in the final analysis.

G. Statistical Analysis

To investigate the impact of the factors *Visibility* (invisible & visible), *Assistance* (without & with), and their interaction on motivation, presence, embodiment, task performance, and visual attention, we performed five 2 x 2 repeated-measures multivariate analyses of variance (RM-MANOVAs). For each RM-MANOVA, the *Visibility* and *Assistance* were considered as independent variables. The three RM-MANOVAs targeting questionnaires (i.e., **motivation**, **presence**, and **embodiment**) considered the questionnaires' subscales as dependent variables. For the task performance RM-MANOVA, the two performance variables **path error** and **lap completion time** were considered as dependent variables. For the visual attention, the **fixation time ratios** over the *Path*, *End-effector*, *Avatar*, *Robot*, and *Others* were considered as dependent variables.

To evaluate whether the independent variables (*Visibility* or *Assistance*) had an effect on the different subscales, performance variables, or the visual attention targets, when a RM-MANOVA indicated a significant effect of an independent variable or interaction, we ran follow-up univariate analyses consisting of a 2 × 2 repeated-measures analysis of variance (RM-ANOVA) for each of the dependent variables. The significance threshold for the RM-MANOVAs was set at $p < 0.05$ and adjusted for the follow-up tests with Bonferroni correction. The Greenhouse-Geisser sphericity correction was applied in the follow-up univariate tests for violations of the sphericity assumption. The reported effect sizes are the partial η^2.

RM-MANOVAs and their univariate following-up tests were performed in *SPSS* version 27. Further exploratory analyses (explained in *Results*) were performed in *R* version 3.6.1 and the module *afex* version 0.28-0.

III. Results

The descriptive statistics are reported in Table I. The results of the five 2 × 2 RM-MANOVAs are listed in Table II. A graphical representation of their changes across *Visibility* and *Assistance* can be found in Fig. 3. The scores of the overall motivation, presence, and embodiment reported in Table I and Fig. 3 were computed by averaging their subscales. The distraction subscale was reversed before being averaged with the other subscales in the overall presence score.

A. Questionnaires

We did not find a significant interaction of the *Visibility* and *Assistance* in **motivation**. We found a trend in the effect of *Visibility*, suggesting that practicing with an invisible robot led to lower motivation compared to a visible robot (Fig. 3, C). Practicing with robotic *Assistance* also led to a significantly higher level of motivation when compared to training without assistance (Fig. 3, A). The univariate tests reflected that the decrease of motivation related to the robot visibility was driven by the *Effort/Importance* IMI subscale ($F = 8.04$, $p = 0.009$). We also observed that the higher motivation observed in conditions with assistance is driven by the higher *Perceived Competence* ($F = 11.98$, $p = 0.002$), *Effort/Importance*

TABLE I
AVERAGED VALUES AND STANDARD DEVIATION OF THE VARIABLES ACROSS *Assistance* AND *Visibility*

Variable	Without Assistance		With Assistance	
	Invisible	Visible	Invisible	Visible
Motivation	4.6 (0.53)	4.72 (0.63)	4.84 (0.58)	4.86 (0.55)
Interest/ Enjoyment	5.63 (1.06)	5.55 (1.02)	5.81 (0.99)	5.84 (0.92)
Perceived Competence	4.62 (1.05)	4.52 (1.24)	4.93 (0.94)	4.86 (1.02)
Effort/ Importance	5.04 (1.01)	5.29 (0.92)	5.36 (1.07)	5.54 (1.00)
Pressure/ Tension	2.02 (1.00)	2.33 (0.98)	2.82 (0.98)	2.61 (1.08)
Trust	5.69 (1.07)	5.89 (1.14)	5.29 (1.32)	5.43 (1.25)
Presence	4.84 (0.74)	4.69 (0.77)	4.20 (0.69)	4.20 (0.59)
Distraction	2.88 (1.02)	3.01 (0.99)	4.01 (0.88)	4.00 (0.79)
Realism	3.88 (0.83)	3.76 (0.66)	3.74 (0.98)	3.68 (0.79)
Involvement/ Control	5.57 (1.32)	5.34 (1.36)	5.45 (1.38)	5.50 (1.26)
Embodiment	5.79 (0.84)	5.72 (0.84)	5.33 (0.86)	5.25 (0.93)
Body Ownership	5.55 (0.96)	5.30 (1.14)	5.02 (1.24)	4.94 (1.19)
Agency	6.02 (0.92)	6.14 (0.84)	5.64 (1.04)	5.55 (1.12)
Path error (cm^2)	5.25 (1.59)	6.20 (3.41)	3.33 (1.40)	3.66 (1.37)
Lap completion time (s)	7.41 (2.25)	7.96 (3.22)	5.66 (1.71)	5.49 (1.92)
Fixation Time Ratio				
Path	0.50 (0.08)	0.53 (0.08)	0.54 (0.07)	0.56 (0.07)
Robot	0.05 (0.03)	0.04 (0.03)	0.06 (0.04)	0.04 (0.03)
Avatar	0.07 (0.05)	0.05 (0.03)	0.05 (0.03)	0.05 (0.03)
End-Effector	0.25 (0.08)	0.24 (0.08)	0.20 (0.07)	0.18 (0.06)
Others	0.14 (0.04)	0.15 (0.03)	0.15 (0.04)	0.17 (0.03)

TABLE II
RESULTS OF THE FIVE RM-MANOVAS

Effect	df	F (Wilks λ)	Effect size	p-value
Motivation				
Assistance	5	9.87	.682	< .001 *
Visibility	5	2.54	.356	.057 •
Assistance:Visibility	5	1.13	.198	.370
Presence				
Assistance	3	11.09	.571	< .001 *
Visibility	3	.32	.037	.808
Assistance:Visibility	3	.73	.080	.544
Embodiment				
Assistance	2	4.62	.262	.019 *
Visibility	2	.86	.062	.437
Assistance:Visibility	2	1.14	.081	.336
Task performance				
Assistance	2	17.77	.578	< .001 *
Visibility	2	1.93	.129	.165
Assistance:Visibility	2	.75	.055	.482
Fixation Time Ratio				
Assistance	4	12.75	.680	< .001 *
Visibility	4	2.47	.291	.072 •
Assistance:Visibility	4	2.52	.296	.067 •

* $p < 0.05$, • $p < 0.1$.

($F = 8.09$, $p = 0.008$), and *Pressure/Tension* ($F = 11.84$, $p = 0.002$) subscales in assisted conditions.

In the **presence** questionnaire, we found neither a significant interaction nor a significant effect for the *Visibility* (Fig. 3, C). However, the robotic *Assistance* resulted in a significant decrease of presence (Fig. 3, A). The univariate tests revealed that this decrease in presence due to assistance is mainly observed in the *Distraction* subscale ($F = 35.44$, $p < 0.001$).

In the **embodiment** questionnaire, we found neither a significant interaction nor a significant effect for the *Visibility* (Fig. 3, C). However, we found that the *Assistance* decreased significantly the embodiment (Fig. 3, A). The univariate tests showed this decrease in both *Body ownership* ($F = 7.07$, $p = 0.013$) and *Agency* ($F = 6.06$, $p = 0.020$) subscales.

1) Subgroup Analysis - Visibility Noticed or Not Noticed: More than half of the participants (57%) did not report having noticed a difference in robot visibility between conditions and only 7% noticed it in both assistance conditions. We performed supplementary analyses to evaluate the effect of *Visibility* and *Assistance* on motivation and presence in the subgroup that noticed the robot visibility (43%) and the subgroup that did not (57%). For each questionnaire and subgroup, we performed the same RM-MANOVAs and univariate tests.

For the subgroup of participants who noticed the visibility difference ($n = 12$), the **motivation, presence, and embodiment** analyses revealed neither a significant interaction nor main effects. However, we found that the *Assistance* showed a trend suggesting that the robotic assistance decreased the presence ($F = 3.61$, $p = 0.058$). The univariate tests showed that the robotic assistance increased the subscales *Perceived/Competence* ($F = 10$, $p = 0.009$) and *Distraction* ($F = 11.65$, $p = 0.006$).

For the subgroup that did not notice the difference in the robot visibility ($n = 16$), the **motivation** analysis revealed a trend suggesting an interaction effect ($F = 2.77$, $p = 0.074$). There was no main effect of the *Visibility*, but the *Assistance* increased the motivation significantly ($F = 6.80$, $p = 0.004$). The univariate tests showed that the interaction impacted the *Pressure/Tension* and the post-hoc t-tests showed that, with an invisible robot, the pressure was perceived higher with the *Assistance* ($F = 14.65$, $p = 0.002$). The univariate tests also reflected that the increase of motivation related to the *Assistance* was driven by the *Pressure/Tension* subscale ($F = 13.92$, $p = 0.002$). For the **presence** and **embodiment**, we found neither a significant interaction nor a significant effect for the *Visibility*. However, the robotic *Assistance* decreased the presence ($F = 7.23$, $p = 0.004$) – from the *Distraction* subscale ($F = 24.26$, $p < 0.001$) – and a trend indicated that it decreased the embodiment ($F = 3.58$, $p = 0.055$) – from a trend of a decreased *Body ownership* ($F = 3.75$, $p = 0.079$) and a significantly decreased *Agency* ($F = 6.89$, $p = 0.029$).

Although the two groups were not directly compared, it is worth noting that the *Trust* values were higher when participants noticed the change in the robot visibility (6.19 ± 0.46) than when they did not (5.11 ± 0.96).

B. Task Performance

We found neither a significant interaction nor a significant difference for the *Visibility* on the task performance (Table II). However, as expected, the *Assistance* resulted in a significant improvement in task performance. The univariate tests showed decrease a in both *path error* ($F = 31.31$, $p < 0.001$) and *lap completion time* ($F = 29.33$, $p < 0.001$) when practitioner with assistance vs. training without assistance.

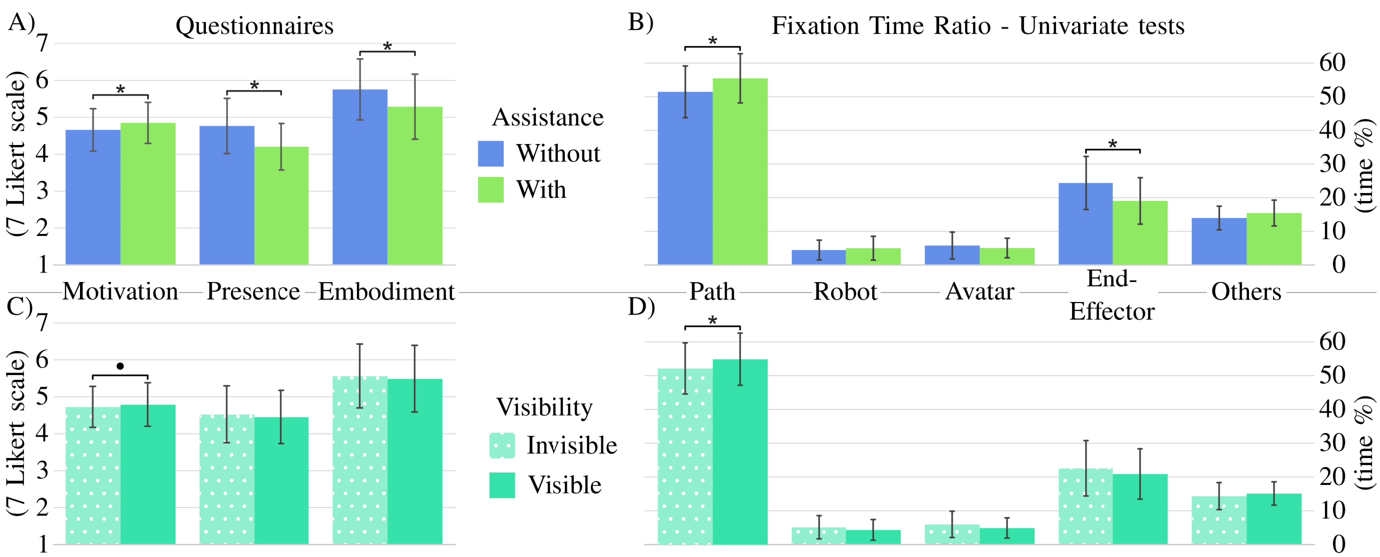

Fig. 3. Effect of A) & B) robotic *Assistance* and C) & D) robot *Visibility* on A) & C) questionnaires and B) & D) fixation time ratio. For the questionnaires, the value shows the average of all subscales. Error bars: ±1*SD*; * $p < 0.05$, • $p < 0.1$.

C. Visual Attention

We only found trends to significance in the interaction and the main effect of the *Visibility*. However, we found a significant main effect of *Assistance* on the visual attention (Table II). The univariate tests did not show any interaction effect in any of the categories. However, for the *Visibility*, we found a significant smaller fixation time ratio when the robot was invisible in the *Path* category (Fig. 3, D; $F = 8.23$, $p = 0.008$). The robotic *Assistance* also significantly increased the relative time participants spent looking at the path (Fig. 3, B; $F = 25.76$, $p < 0.001$), while shortened the relative time they looked at the end-effector ($F = 41.24$, $p < 0.001$).

IV. Discussion

In this study, we investigated how healthy participants' motivation, presence, embodiment, motor performance, and visual attention were affected when an assistive robotic device they were attached to was visible or not in immersive VR using an HMD during a path-tracing task. Twenty-eight healthy participants performed the same tracing task with four different conditions (*Invisible/Visible robot* x *With/Without assistance*).

A. The Robotic Assistance, Rather Than the Robot Visibility, Enhanced Participants' Motivation

We expected that, when participants were not assisted during the task, their motivation would increase with an invisible (vs visible) robot, due to an increased perceived competence. However, contrary to our expectations, the differences in motivation between the *Invisible* and *Visible* conditions were not affected by the provided assistance – i.e., we did not find an interaction effect between *Visibility* and *Assistance*. We found, however, a non-significant trend that suggested a slightly higher motivation with the visible robot. This seems to be due to a higher *Effort/Importance*, rather than higher *Interest/Enjoyment*, this later subscale being generally assumed to reflect the intrinsic motivation [39].

Our results extend previous work on enhanced perception of participants' performance – e.g., by providing robotic assistance [23], [25], [44] or visually enhancing the performance within the VE [24]. As in [23], [44], the assistance did not result in enhanced *Interest/Enjoyment*, but in a significant, albeit small (0.32), increase in the *Perceived Competence*. As there was no significant interaction effect, this attribution seemed to be independent of the robot's visibility in the VE. This might be explained by findings showing that participants' level of intrinsic motivation is higher when the task is slightly too demanding, compared to performing perfectly [45], [46]. Thus, although applying assistance enhances the perceived competence, it might not have a positive effect on the intrinsic motivation if it results in a too good performance – the so called "boredom channel" [47]. An attribution of this external assistance to participants' competence was also reported by [25]. However, they conclude it from the absence of significant difference in *Agency*, whereas, in our experiment, we found a decrease in agency with the assistance (see subsection IV-B). Therefore, even if the participants felt less in control of their own movements, they might still have perceived the increased performance as resulting from their own competence, raising concerns about measuring the performance attribution with *Agency*. Interestingly, and contrary to our expectation, visually hiding (vs showing) the source of the movement corrections (i.e., robot) did not help users to further attribute the assistance as their own.

B. The Robotic Assistance, Rather Than the Robot Visibility, Hindered Presence and Embodiment

We further expected that, with the robotic assistance, the participants' feeling of presence and embodiment would decrease if the robot was invisible versus visible due to sensory mismatch. However, we did not find a main effect of *Visibility*, nor an interaction effect with *Assistance* on the subjectively reported presence nor the embodiment. Moreover, when the robotic assistance was applied, the overall values of the presence and embodiment questionnaires decreased (respectively, -0.56 and -0.47) compared to non-assisted training. Together, and contrary to our expectations, the robotic assistance hampered the presence and embodiment and visually explaining the force by displaying the robot in the VE did not seem to compensate this effect.

Our results complement the body of knowledge about the impact of sensory mismatches on presence and embodiment [26], [48]–[50]. For example, the absence of haptic feedback was found to reduce the sense of presence in an object manipulation task in VR [48]. Similarly, spatial – but not temporal – mismatches between haptic and visual information were found to deteriorate presence [26]. Unlike the aforementioned studies, it is worth noting that the forces the users felt in our study were not provided to haptically render virtual elements, but to assist the participants. Therefore, providing a visual origin of the assisting force (i.e., the robot) might not solve the potential sensory conflict. Although participants could see that the force might come from the robot, they still did not receive information about when the force was applied nor why.

We did not observe a main effect of the robot *Visibility* in presence. This is in line with another study, where participants changed gears in a driving simulator with a real paddle-shift while they saw their avatar using either the same paddle-shift (congruent) or a stick-shift (inconcruent), and found that the (in)congruency did not affect presence [50]. Nevertheless, to the best of our knowledge, our study is the first to show that mismatches arising from missing (and not just erroneous as in [50]) visual elements might not affect the sense of presence.

Our finding of reduced embodiment when participants were assisted differs from previous literature [25]. For example, Endo and colleagues [25] found no significant difference in agency when assistive forces were applied to correctly perform a reaching task, compared to performing without assistance. However, their performed task – a reaching task – and type of assistance – a force with a constant profile towards the reaching goal – differ from our tracing task and path control assisting strategy. The assistance from our path controller – selected as it is a common form of assistance in robotic rehabilitation [27], [36] – might have been perceived as less natural by participants, and thus more noticeable, as it applied forces proportional to the distance to the path and towards the path, rather than towards the participants' intended forward direction. Furthermore, although our assistive forces increased the participants' performance – i.e., reduced the path error and the lap completion time – the unnatural behavior experienced in the sharp curves may have increased the participants feeling that the robot interfered with their performance, as previous research showed that different types of controllers have divergent effects on agency [44], [51].

C. Visual Attention & Inattentional Blindness

The visual attention analysis revealed that when participants were assisted (vs not), they looked less at their virtual hand and more at the path. A potential explanation could be that the assistance allowed participants to better anticipate their movements, reducing the need for precise real-time on the spot corrections. Although the main effect of the robot visibility on the fixation time ratio did not reach significance, participants seemed to spend more time looking at the path when the robot was visible (vs not). However, this could be due to occlusions of the task elements (path and coins) by the animation of the virtual forearm cuff and the robot. Participants seemed not to be visually more attentive to the robot's space when it was visible (vs not), which is coherent with the fact that most participants did not report to have noticed the difference in the robot visibility.

Interestingly, the group which did not notice the difference in the robot visibility reported higher pressure and tension values (subscale of the IMI) when they were assisted (vs not), notably when the robot was invisible. Thus, noticing the presence or absence of the robot might help participants to better understand the system they interact with, resulting in less tension during the task, especially when the felt forces came from an invisible source. This hypothesis is coherent with the observed lower trust in the system reported by the group which did not notice the differences in the robot visibility compared to the group that noticed the difference. However, it is worth noting that these supplementary analyses on the subgroups were performed with a small sample size, especially for the group that noticed the difference at least once during the experiment, and results should be taken cautiously.

Even if the robot (including the forearm cuff) was clearly visible and not occluded by other virtual elements, the number of participants who noticed the difference in the robot visibility was rather small. This might be due to the so called *inattentional blindness* – i.e., *"the failure to notice a fully-visible, but unexpected object because attention was engaged on another task, event, or object."* [52] – as users were focused on the task and might not have been attentive to task-irrelevant elements in the VE [53]. This is in line with a study where participants were asked to perform a dummy assembling task in an immersive VE while wearing an HMD [54]. Authors progressively changed the VE environment from a garden to an assembly workshop. In total, 84% of the participants noticed less than half of the transitions, with 37% of the users not noticing any changes. However, the observed *inattentional blindness* does not compromise our results, as it does not seem to be the sole reason behind the lack of a main effect of the robot visibility on the users' motivation, presence, embodiment, and visual attention; even in the group of participants who noticed the visual change, no significant differences were observed.

D. Implications for Stroke Neurorehabilitation

An emerging body of literature advocates for the use of more immersive VR-based clinical interventions, such as HMDs, as they might enhance presence, embodiment, motivation and engagement [15], [55]–[57], and motor performance [14] compared to the standard computer screens or televisions mainly used in current interventions [58]. However, this literature did not evaluate the impact of the robot's invisibility in the VE when HMDs are used during robotic-based therapy.

Our results, although only obtained in healthy participants, show no drawbacks from the sensory mismatch associated with the invisibility of the assisting robot. Thus, HMDs could potentially be used in combination with robots without the constraint of realistically representing the robot in the VE. Our results also indicate that care should be put into developing assisting controllers; although they might enhance motivation, they could hamper the patients' presence and embodiment.

Performing the experiment with a healthy population allowed us to have a first understanding of how the sensory mismatch (between the felt but not seen robot) in robotic-assisted VR tasks might impact the users, with less inter-individual variability than with a brain-injured population [59]. Nevertheless, the impact of immersive VR together with robotic assistance on neurological patients needs further investigation. For example, sensory impairments are common after stroke [60]. Therefore, it is possible that patients feel less the robotic forces, which could ultimately reduce the occurrence of the sensory mismatch. Stroke patients also often present attentional deficits [61], potentially affecting inattentional blindness. Reproducing a similar study with brain-injured patients is, therefore, of high relevance for future clinical research.

E. Study Limitations and Future Research

Our experimental design suffers from several limitations. First, the duration of each condition (~3 minutes) was rather short compared to other studies [12], [13]. Although the reported embodiment and presence values were relatively high, a longer VR exposition time may have further enforced these user affects. However, longer exposition times could have also resulted in accommodation effects to a condition that could have been carried over to the following conditions – e.g., the questionnaires breaks between conditions might have been too short and carry-over effects might have influenced the embodiment and presence ratings. In addition, this potential limitation was minimized by balancing the order of the different conditions. Second, although the assistance from our path controller enhanced the participants' performance, the unnatural behavior on sharp curves might have affected participants' reporting. Third, the order of the conditions was balanced but not completely randomized (i.e., the two conditions with the same assistance type were always consecutive), which might also have affected our results. Finally, the task performance was only assessed in terms of path error and lap completion time, as participants were requested to follow the paths as fast and precisely as possible. However, other performance metrics (e.g., smoothness) could have been used and different results observed.

Finally, in the field of neurorehabilitation, different robot architectures (e.g., end-effector vs exoskeleton) and controller strategies (e.g., weight support, model predictive control, error augmentation) are employed [27], [28]. Future similar studies with other robotic architectures and/or control strategies are needed to understand how our findings generalize to different rehabilitation setups found in clinics.

V. Conclusion

This study investigated the impact of the visibility of an assisting and non-assisting rehabilitation robot in immersive VR on motivation, presence, embodiment, and visual attention in healthy participants performing a path-tracing task. Our results are of important significance, as we demonstrated that rehabilitation robots do not need to be visually represented in the VE even when they assist users' movements. This may simplify the implementation of effective clinical training protocols in robotic neurorehabilitation and enhance therapy outcomes. Importantly, we showed that care should be put when developing assisting controllers, as the assistance could hamper patients' affect.

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