



OPEN A surprise induced by a visual-haptic illusion in virtual reality can lead to motor improvement

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This study assessed the preliminary results of an experimental protocol evaluating the impact of positive expectations on fingertip-to-floor distance during forward bending. Thirty-six participants were assigned to three groups, each receiving a sham physical manipulation in Immersive Virtual Reality (IVR). The first group received a neutral statement about the manipulation's efficacy, while the second and third groups were told the manipulation would improve forward bending, emphasising its fictitious positive effect to increase expectations for a beneficial motor improvement. Additionally, the third group also experienced a visual-haptic illusion, by lifting a tile in front of participants and raising the floor in the virtual scenario, creating the belief of reaching the floor thanks to the received manipulation. Fingertip-to-floor distance was measured at baseline, immediately after the manipulation (after-effect), and five minutes later (follow-up). Differences between baseline and after-effect/follow-up distances represented the gained distances. Only the third group, which experienced the combined effect of positive verbal statement reinforced by the visual-haptic illusion, showed a significant increase in gained distance during the after-effect and follow-up phases compared to the neutral statement group. These findings support the potential of this multifactorial intervention to promote motor improvement by enhancing positive expectations.

Keywords Virtual reality, Placebo effect, Motor improvement, Bayesian brain, Contextual factors, Computer simulation

Human motion is the result of the interaction between the musculoskeletal apparatus and the central and peripheral nervous systems¹. They cooperate via a complex integration of sensory-motor, emotional and cognitive inputs, resulting from top-down and bottom-up processes² to adapt human motor responses to everyday tasks^{3,4}. The context in which movement occurs is characterised by internal (e.g., psycho-biological aspects like personality traits and genetics) and external (e.g., physical and social aspects of the environment) factors. These factors, together with previous individual experiences, social interactions, beliefs, and internal states play a key role in influencing physiological and behavioural responses^{5–8} through an internal inferential model that can be linked to the so called “Predictive Processing” theory^{9,10}.

The Predictive Processing model describes the brain as a dynamic system^{11–14} continuously aiming to minimise predictive errors by comparing expected inputs (i.e., expectations) with the afferent multi-sensory stimulation to optimise interaction with the environment in terms of perception, decision making, and motor control^{15,16}.

Various formulations of predictive processing have been proposed¹⁷, ranging from early hierarchical models^{18–20} stemmed from Bayesian theory^{21,22} to more comprehensive and dynamic frameworks^{11,23,24} that extend beyond brain-based computation to incorporate dynamic interactions among the brain, body, and environment.

In this context, the “Perceptual Inference” model provide a possible method to reduce prediction errors^{25,26}. In this model, more weight is given to actual afferent multi-sensory information than to “Priors” (i.e., the previously consolidated view of the situation), resulting in new “Posteriors” (i.e., an updated view of the situation) used to interpret future events. Additionally, research indicates that verbal instructions can influence motor responses, even without prior direct experience of an action's effects²⁷, modulating attention, response selection, and cognitive biases²⁸. These findings suggests that verbal cues are integrated with sensory experiences²⁹ to shape and adjust Priors³⁰, influencing how individuals interact with the environment.

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In recent years, Immersive Virtual Reality (IVR) has been widely exploited in research^{31–33} as a promising tool that can alter the contextual perception of the person immersed in terms of temporal and spatial references³⁴. Thus, from the perspective of the Predictive Processing framework, IVR can be seen as an effective method for influencing a person's expectations (Priors), ultimately affecting their functional outcomes (Posteriors).

Here, relying on the principles of Perceptual Inference, we propose that, IVR can effectively shape a person's pre-existing movement expectations, leading to improved movement strategies and better motor outcomes. This general idea could be especially useful in actively challenging negative expectations about one's own health that can lead into erroneous beliefs aimed at avoiding pain, known as fear-avoidance beliefs³⁵. This negative mindset can contribute to an irrational fear of physical movement, also known as kinesiophobia³⁶, leading to a reduced mobility. This phenomenon is well documented in musculoskeletal conditions and particularly for chronic low back pain³⁷.

Motivated by the potential for future clinical application in chronic low back pain, and considering the difficult that this population experiences during lumbar movements³⁸, we conducted a preliminary pilot study on healthy people to test whether positive verbal feedback and immersive visual-haptic stimuli could enhance expectations (priors) and improve fingertip-to-floor distance in a forward bending exercise.

Methods

Trial design

This study was conducted following the Declaration of Helsinki and it is here reported according to the Consolidated Standards of Reporting Trials - CONSORT (see Supplementary file) for pilot and feasibility trial³⁹. Ethical approval was obtained from the Ethics Committee for University Research (CERA: Comitato Etico per la Ricerca di Ateneo), University of Genova (approval date: 12/11/2020; CERA2020.23).

Participants

Participants were recruited from a convenience sample of healthy people. Eligibility was determined based on the following inclusion criteria: (a) no history of neurological, vestibular, rheumatic, or musculoskeletal diseases, and no reported low back pain in the previous six months that impacted daily activities, work (e.g., absenteeism), or necessitated medical or physiotherapy intervention; (b) aged between 18 and 55 years old, and (c) the ability to reach a distance of at least 25 cm from the floor (maximum extension of the movable tile, see Chap. 2.3 Intervention), as measured by the Fingertip-to-Floor Test⁴⁰. Informed consent was presented in a written form and obtained from all participants before the experiment.

Sample size

Considering the exploratory nature of the study, a sample size of 12 participants per group was recruited, as suggested by Julious⁴¹.

Blinding procedure

Participants did not know which group they were assigned to. As reported above, all participants received before the onset of the study the same explanation about the experimental aims.

Interventions

Experimental protocol

Our study followed an experimental design often used in placebo research, which aims at exploring the role of participants' beliefs in an intervention⁴². This is accomplished by providing a population with an ineffective treatment (or no treatment) without their knowledge, to examine the impact of individual expectations and beliefs alone. In our case, to cover the real purpose of this study, consisting in the administration of positive expectations induced by different verbal and perceptive virtual stimuli to reduce the fingertips-to-floor distance during forward bending, a fictitious clarification of the study was provided to all participants once they arrived at the laboratory:

“The goal of this study is to evaluate whether Virtual Reality can be used as a tool to measure in real-time, changes in the mobility of the spinal column. We will take the measurements both with a manual instrument and with virtual reality, to see how much difference there is between the accuracy of these two measurements.”

The real aim of the study was disclosed to each participant only at the end of the experimental session.

All participants performed a series of forward bends while standing on a rigid cubic structure of (50×50×7 cm). This solution was adopted to increase the distance from the floor to facilitate the measurements also in those participants that nearly reached the ground. Starting from a standing stance position with the feet together, the participants were explicitly verbally instructed to bend forward maintaining the elbows and the knees extended, with the palms of the hands together, reaching a target represented by a black “X” mark located at 20 cm from the tip of the toes, positioned along a line painted on the floor. Each forward bend was accompanied by the experimenter's indications about its execution in both modality and timing (“go down slowly - bend as much as you can - stay - up”).

Following these directives, the participants executed 30 warming-up forward bends before the experiment started. The first 15 were utilised as an additional exclusion criteria to make sure that the participant did not easily reach the floor (potentially resulting in a ceiling effect in the measurements), and the last 15, executed before the beginning of the study, to adjust for the eventual mobility gain related to the continuous repetitions of the task⁴³.

After, each participant performed four consecutive trials (Baseline, Intervention, After-Effect, and Follow-Up) according to the specific allocation group: (i) Neutral Expectation Group (G0), (ii) Positive verbal Expectation Group (G+), and (iii) Visual-Haptic illusion + Positive verbal Expectation (G++). Participants were

assigned to each group based on their arrival order, with groups being filled consecutively. The four trials were performed in the immersive virtual scenario (see technical characteristics of the system at 2.3.2 – *Immersive Virtual Reality (IVR) system and virtual scenario*). Each individual stood on a tile with four different floor panels around it, positioned orthogonally to each other, as displayed in Figure 1. The person was asked to turn towards each different panel based on the specific phase of the trial of the trial (Baseline, Intervention, After Effect and Follow-Up). Specifically, the participants performed five forward bends toward each tile, with the experimenter positioned behind the participant to verbally guiding them during the experiment. A sham physiotherapy manoeuvre, consisting of four pressures of 40 N for 10 s. each in four bony sites not directly involved in the back movement (left and right posterior-superior iliac spine, and left and right medial margin of the spina scapulae) was executed in all groups before performing the experimental task towards the “Intervention” tile. The physiotherapy sham manoeuvre was standardised with an algometer Wagner Force One™ Digital Force Gage (Wagner, Greenwich 2020, USA) and paired with a verbal statement related to its efficacy different for each group.

The experimental protocol differentiated for each group is thoroughly reported in Table 1.

Briefly, in G0 group, the execution of the sham physiotherapy manoeuvre was accompanied by a neutral verbal statement regarding its effectiveness and stated by the experimenter immediately after the end of the manoeuvre. On the contrary, the groups G + and G ++ received a positive verbal stimulus regarding its efficacy.

Furthermore, only in the G ++ group, after the sham manoeuvre and the positive verbal stimulus, the tile in front of the participants was subtly raised using a mechanical jack, without their knowledge, creating the illusion that they had successfully touched the floor (Fig. 2). The level of the tile was raised to match the fingertip-to-floor distance each participant reached during the Baseline measurement. Independently from the groups, all the sham manoeuvres were conducted by the same experimenter trained by specialised physiotherapists to apply pressures and recognise the specific anatomical marks. Moreover, the same experimenter was also in charge of the assessments of the fingertip-to-floor distance across all participants and experimental trials. A lounge music was played in the background of the laboratory and through the earphones of the head-mounted display in the IVR system. The volume was kept low to allow participants to hear the experimenter’s instructions and was increased only during the activation of the mechanical jack to mask the noise coming from the tile’s movement (Table 1). The same lounge music was played continuously through the earphones of the Head-Mounted Display (HMD) for the entire duration of the study and for all groups to standardize the intervention. After the experimental session and the disclosure of the real purpose of the study, participants were asked to report if they become aware of the illusion and if they had heard any noise during the lifting of the tile during the repeated performance of the task. All participants confirmed that they did not notice the movement of the tile, reporting that the music volume was loud enough to mask any sound produced during its lifting.

Immersive virtual reality (IVR) system and virtual scenario

The immersive environment was delivered through the HTC Vive Pro system. This system is based on a full-body tracking technology (SteamVR 1.0 tracking) able to register synchronously the position and orientation of different trackable elements and translate this information into the virtual scenario for realistic visual-haptic feedback⁴⁴. The implemented apparatus was calibrated over a 2,5 × 2,5 m and included a Vive PRO HMD, two SteamVR 1.0 Lighthouse base stations, and three Vive trackers 2.0 (Valve, Washington, United States, 2018). The HMD was connected to a PC in wireless configuration and participants’ movements were recorded through two Vive trackers positioned with velcro straps on the back of their hands. The virtual scenario (Fig. 3B) was a 1:1 reconstruction of the laboratory in which the participants performed the experiment (Fig. 3A), designed in Unreal Engine 4.25.4.

In this environment, the virtual point of view of the user was adjusted according to the registered height position of the third VIVE tracker positioned over a movable panel on the floor. A schematic representation of the experimental setup is reported in Fig. 3D. To adjust the level of the virtual floor across the experimental trials,

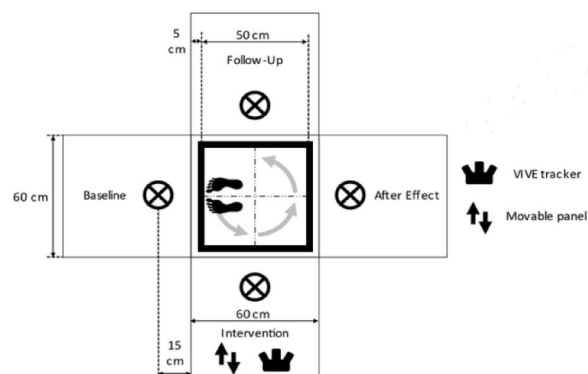


Fig. 1. Tracking area in which the study was performed. Participants executed the whole study by turning inside the area identified by the black square, representing the top view of the rigid cubic structure. The task involved participants performing a forward bending movement and reaching with their hands towards the black X. This task was performed at three different time intervals: Baseline, After-Effect, and Follow-Up.

Baseline	(G0, G+, G++) Participants executed 5 forward bends. The level of the floor was maintained at the same level as the real one. During the last bending, the fingertip-to-floor distance was measured by a tape measure.		
Pause (1 min)	(G0, G+) To standardize the intervention across all groups, participants were asked to wait for one minute in an upright stance position under the fictitious pretext that “data needed to be loaded into the system.” During this time, a black dummy loading screen was displayed on the head-mounted display, and the music volume of the virtual scenario was increased.		(G++) Participants were asked to wait in an upright stance position under the fictitious pretext that “data needed to be loaded into the system”. During this time, the tile was lifted to match the fingertip-to floor distance reached by the participant during Baseline, and a black dummy loading screen was displayed on the head-mounted display The music volume of the virtual scenario was increased to cover the noise of the moving tile.
Intervention	(G0) Immediately after the pause, participants received a sham manoeuvre accompanied by the following verbal stimulus related to its efficacy: “Now I am going to apply this tool (digital algometer) on different points of your back after which we will resume the measurement, both with the manual method and with virtual reality.” Subsequently, participants executed 5 forward bends. The level of the virtual floor was maintained at the same level as the real one.	(G+) Immediately after the pause, participants received a sham manoeuvre accompanied by the following verbal stimulus related to its efficacy: “Through this manoeuvre, I will treat the main trigger points that reduce the flexibility of the spine and by stimulating them your mobility will increase and you will be able to bend forward more.” Subsequently, they executed 5 forward bends with the virtual floor maintained at the same level as the real one.	(G++) Immediately after the pause, participants received a sham manoeuvre accompanied by the following verbal stimulus related to its efficacy: “Through this manoeuvre, I will treat the main trigger points that reduce the flexibility of the spine and by stimulating them your mobility will increase and you will be able to bend forward more.” Subsequently, participants performed 5 forward bends with the virtual floor raised at the height of the tile lifted in front of the participants.
Pause (20 s)	(G0, G+) A black dummy loading screen was displayed on the head-mounted display, and the music volume of the virtual scenario was increased.		(G++) A black dummy loading screen was displayed on the head-mounted display, and the music volume of the virtual scenario was increased. The level of the virtual floor was re-settled at the same level as the real one.
After-Effect	(G0, G+, G++) Immediately after the pause, participants performed 5 forward bends. The virtual floor was maintained at the same level as the real one. During the last bending, the fingertip-to-floor distance was measured by a tape measure.		
Pause (5 min)	(G0, G+) Participants were asked to wait five minutes in an upright stance position, before starting the Follow-Up trial. To standardize the intervention across all groups, for the first minute, a black dummy loading screen was displayed on the head-mounted display, and the music volume of the virtual scenario was increased.		(G++) Participants were asked to wait five minutes in an upright stance position, before starting the Follow-Up trial. For the first minute, a black dummy loading screen was displayed on the head-mounted display, and the tile was lowered while the music volume of the virtual scenario was increased.
Follow-Up	(G0, G+, G++) After the pause, participants performed 5 forward bends. The virtual floor was maintained at the same level as the real one. During the last bending, the fingertip-to-floor distance was measured by a tape measure		

Table 1. Experimental protocol differentiated by group (G0, G+, G++).

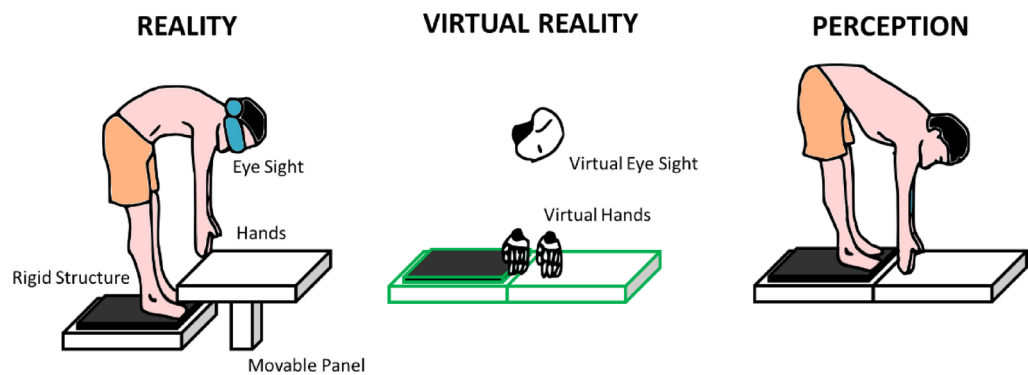


Fig. 2. Participant’s Perception of the Forward Bending Task during the Visual-Haptic Illusion in Immersive Virtual Reality (G++ Group). (On the left) Visual-haptic illusion implementation. (On the center) Virtual simulation experienced by the participant. (On the right) Personal perception intended to be elicited in participants experiencing the visual-haptic illusion.

the laboratory environment was temporarily masked by displaying a black dummy loading screen (Fig. 3C) with increased background music volume to conceal the sound of the tile movement and the change in the virtual viewpoint of the scene.

Outcome measurements

The main outcome measure of the present study were the gained distance values, obtained for the three different groups (G0, G+, G++) by subtracting the fingertip-to-floor distances obtained in the Baseline with the ones reached at the After-Effect and Follow-Up conditions, as reported below:

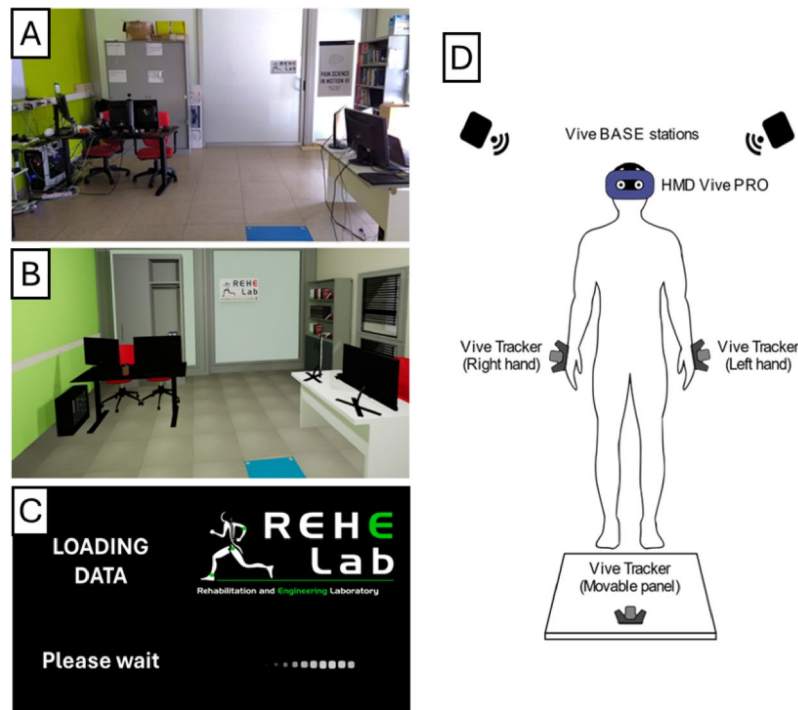


Fig. 3. **A** Real laboratory and **B** its virtual reconstruction. **C** Loading screen displayed during the tile movements. **D** Experimental setup of the virtual reality system.

$$\Delta_{ae/b} = x_b - x_{ae}$$

$$\Delta_{fu/b} = x_b - x_{fu}$$

Where the x is the fingertip-to-floor distance reached from the floor and the subscripts b , ae , and fu represent the three experimental trials, namely, baseline, after-effect, and follow-up. Out of the five forward bends performed in each trial, the fingertip-to-floor distances were measured only during the final bend using a tape measure.

Statistical analysis

Statistical analysis was carried in Python 3 (Python Software Foundation, version 3.13.1. Available at <http://www.python.org>). All explanatory figures were created with GNU Image Manipulation Program 2.10.24 (GIMP) and with Inkscape 1.1.2 (Inkscape Project, 2020. Inkscape, Available at: <https://inkscape.org>).

Descriptive analysis (age, BMI, gender they identified with) was carried out and reported as mean and standard deviation or percentages as frequencies. The gained distance values and the fingertip-to-floor distances were reported as median (Q2) with the first quartile and third quartile [Q1, Q3] as indexes of dispersion since data did not follow a normal distribution, after visual inspection of the Q-Q plots (statsmodels module: qqplot)⁴⁵.

Then, we used the Kruskal-Wallis H-Test to compare the gained distance values [cm] obtained during the After-Effect and the Follow-Up in respect to the Baseline. The post-hoc analyses were performed using pairwise Mann-Whitney U-Tests.

The significance acceptance level for pairwise comparison was adjusted to 0.0125 using the Bonferroni Correction⁴⁶, with k representing the number of comparisons ($k = 3$). Effect sizes were calculated as rank biserial correlation coefficients⁴⁷. We used bootstrapping (500 replications) to compute 95% CI of the effect size across the different interventions. The Python script of the statistical analysis is reported in the Supplementary Data file.

Results

A convenience sample of 58 eligible participants was considered for inclusion and screened for eligibility. Among them, 6 (10,3%) were enrolled to optimise and test the first draft protocol of the study, 2 (3,4%) were excluded for difficulties related to experiences with an IVR environment, such as lack of air and dizziness, and 14 (24,1%) were excluded since they easily reached the floor during the 30 warming-up flexions. Ultimately, thirty-six participants (62%) were considered eligible and included in this study. They were equally assigned to each experimental group (G0, G+, G++). Descriptive characteristics of the three experimental groups are presented in Table 2.

Table 3 reports the medians [Q1, Q3] of the different parameters explored. Overall, the Kruskal-Wallis H-Tests, showed a statistical difference, in terms of gained distance values in relation to the Baseline, between all the different groups in the After-Effect, $p = 0.011$, and in the Follow-Up, $p = 0.030$. Post-hoc Mann-Whitney U-tests showed that the gained distance values at the After-Effect and the gained distance values at the Follow-

Groups	G0	G+	G++
N	12	12	12
Age: Mean $\pm$ SD	26 $\pm$ 3	27 $\pm$ 5	25 $\pm$ 7
BMI: Mean $\pm$ SD	23.88 $\pm$ 3.99	24.99 $\pm$ 2.97	21.93 $\pm$ 1.80
Gender: W (%); M (%)	5(42); 7(58)	5(42); 7(58)	6(50); 6(50)

Table 2. Participants' descriptive analysis. G0, neutral expectation group; G+, positive expectation group; G++, Visual-haptic illusion + Positive verbal Expectation Group; N, number; SD, Standard Deviation; BMI, Body Mass Index; M, Men; W, Women.

Parameters	G0 (N=12) [cm]	G+ (N=12) [cm]	G++(N=12) [cm]
x_b	12.7 [8.7, 19.2]	13.0 [10.6, 16.6]	18.9 [17.9, 19.9]
x_{ae}	11.5 [7.9, 20.2]	10.75 [6.9, 14.4]	15.5 [13.4, 16.4]
x_{fu}	13.0 [8.0, 20.7]	12.0 [6.5, 16.4]	17 [14.6, 17.6]
$\Delta_{ae/b}$	0.8 [− 0.6, 2.0]	2.2 [1.0, 3.2]	3.2 [2.4, 5.5]
$\Delta_{fu/b}$	0.0 [− 0.7, 1.4]	0.7 [− 0.1, 2.6]	1.7 [1.3, 3.1]

Table 3. Descriptive analysis for the fingertip-to-floor distances obtained in the different time periods (x_b , x_{ae} , x_{fu}), with relative gained distance values ($\Delta_{ae/b}$, $\Delta_{fu/b}$). Parameters are differentiated by group and reported as median [Q1, Q3]. N = number of participants per group; x_b , fingertip-to-floor distance (baseline); x_{ae} , fingertip-to-floor distance (After-Effect); x_{fu} , fingertip-to-floor distance (Follow-Up); $\Delta_{ae/b}$, gained distance at the After-Effect respect to the Baseline; $\Delta_{fu/b}$, gained distance at the Follow-Up respect to the baseline.

Group comparison	Dependent variable	Mann-Whitney U	Effect Size (r_b) [95% CI]
	$\Delta_{ae/b}$		
G0 vs. G++		$p=0.018$	− 0.663 [− 0.927, − 0.278]
G0 vs. G+		$p=0.244$	− 0.418 [− 0.778, 0.063]
G+ vs. G++		$p=0.314$	− 0.383 [− 0.785, 0.080]
	$\Delta_{fu/b}$		
G0 vs. G++		$p=0.029$	− 0.633 [− 0.931, − 0.260]
G0 vs. G+		$p=0.576$	− 0.324 [− 0.726, 0.087]
G+ vs. G++		$p=0.578$	− 0.301 [− 0.754, 0.170]

Table 4. Mann-Whitney U-Tests comparisons of the gained distance values obtained in the After-Effect and the Follow-Up with respect to the baseline. G0, neutral expectation group; G+, positive expectation group; G++, Visual-haptic illusion + Positive verbal Expectation Group; $\Delta_{ae/b}$, gained distance at the After-Effect respect to the Baseline; $\Delta_{fu/b}$, gained distance at the Follow-Up respect to the baseline.

Up differ only in the comparison between the G0 and G++ groups. The gained distance values did not differ in any other group comparison (Table 4). Boxplots for the gained distance values for all three experimental groups are reported in Figs. 4 and 5 respectively.

Discussion

The main finding of this study is that the use of the IVR system could be a valid and safe instrument to modify the fingertip-to-floor distance during forward bending task in a cohort of healthy people. Hereafter, we are discussing the preliminary results of this study, its future applications in research, and the possible improvements of the present protocol for forthcoming clinical trials.

Our hypothesis was that a positive modification of participants' expectations induced by the belief of being able to touch the floor would translate into a modification of their motor strategy, enhancing their forward bending and consequently reducing the fingertips-to-floor distance. Our results partially align with our initial hypothesis, highlighting that the verbal and the visual-haptic manipulation can reduce the fingertip-to-floor distance in a cohort of healthy individuals. Specifically, the G++ group and the multisensory nature of its specific intervention (i.e., verbal manipulation, visual-haptic illusion) showed a significant improvement in terms of gained distance values from the G0 group. The role played by inducing positive expectations to increase the performance of motor tasks is in line with a broad array of previous studies^{48–54} suggested that the expectancies related to the occurrence of non-volitive responses, called response expectancies, and those related to the

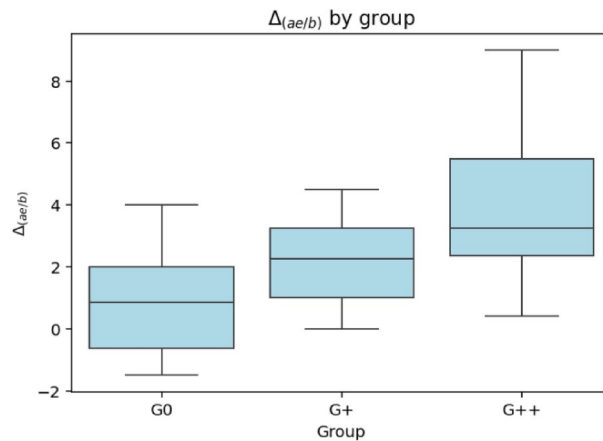


Fig. 4. Boxplot of the gained distance value obtained in the After-Effect for each of the experimental groups. The central line within the box represents the median, while the edges of the box correspond to the first (Q1) and third (Q3) quartiles. The whiskers extend to the most extreme data points within 1.5 times the interquartile range ($\pm 1.5 \times \text{IQR}$) from the lower and upper quartiles.

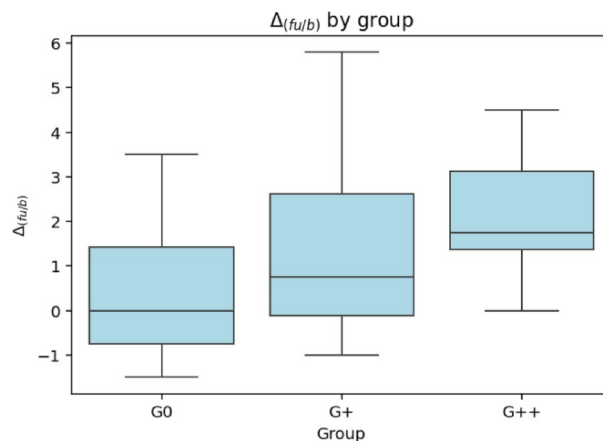


Fig. 5. Boxplot of the gain distance obtained in the Follow-Up for each of the experimental groups. The central line within the box represents the median, while the edges of the box correspond to the first (Q1) and third (Q3) quartiles. The whiskers extend to the most extreme data points within 1.5 times the interquartile range ($\pm 1.5 \times \text{IQR}$) from the lower and upper quartiles.

own self-efficacy, named self-efficacy expectancies, significantly contribute to the overall placebo and nocebo response. According to Kirsch's conceptualisation, it is possible to speculate that the presence of these two kinds of expectancies affected the magnitude of the improvement in the gained distance values via a summative effect.

Indeed, in the G++ vs. G0, the combination of a verbal manipulation and the visual-haptic illusion might have induced in the participants a stronger belief that they can successfully reach the floor. Hence, the improvement in the motor performance through the visual-haptic illusion may have tapped into the abovementioned self-efficacy expectancies. Moreover, this fast recalibration of the information might be elicited by the surprise or “wow effect”⁵⁵, induced by the unexpected possibility of touching the floor as a result of the visual-haptic illusion. Classically, surprise is considered as an emotion that occurs when there is a discrepancy between what is perceived and what is expected, and induces the recalibration of our beliefs, expectations, and behaviours^{56,57}, inducing specific cortical activations⁵⁸ and cognitive responses⁵⁹. The sense of surprise can also be interpreted through the framework of predictive processing⁵⁷, in which the mismatch between expectations and incoming sensory information must be resolved. As suggested by the cognitive-evolutionary model of surprise⁵⁷, the schemas that control perception and actions are continuously updated at an unconscious level through the comparing of the incoming information to those possessed (belief).

Moreover, while the G0 group with neutral expectancy reported the lowest gained distance value, the G+ group, where the response expectancy was induced through a positive verbal stimulus provided by the experimenter, improved their gained distance values (even if not statistically different) from G0. However, the 95% CI in the effect size in G+ vs. G0 was pretty close to a positive value. Despite we did not find a statistical

difference between G + and G ++ group, probably because of a sample size related problem, a trend was seen in favour of G ++ in the comparison of G + and G0.

The results presented should be appraised with caution in the light of specific limitations inherent in the exploratory character of this study. Since this work wanted to test the experiment and its possible outcomes while providing valuable information for improving future research, we have reported the limitations encountered and proposed potential solutions to address them.

The main limitation of this work lies in the measurement methodology of the fingertip-to-floor distance, performed manually by a single experimenter. The experimenter was aware of which group the participants belonged to, and this might have influenced the results with a potential bias. Future developments of this experimental methodology should consider blinding the assessor and the statistician to reduce possible measurement biases. Additionally, previous research showed that fingertip-to-floor test in healthy people has a high degree of variability, with coefficients of variation ranging from 14 to 76%^{40,60,61}. The promising results of our study might justify the use of more sophisticated and expansive measurements technologies (e.g., optoelectronic motion capture systems).

Furthermore, during the time of the experiment, the existing literature on the accuracy of VIVE Trackers for measuring positions using the SteamVR 1.0 tracking systems presented inconsistent findings⁶². Given this variability and the difficulties associated with a repeatable position of the rather cumbersome trackers on the back of the hand, we made the decision to simply rely on manual assessment of fingertip-to-floor distance. Given the recent advancements in motion tracking technology for IVR systems⁶³, future studies should implement objective methods to evaluate not just the distance achieved from the floor, but also the full-body kinematics during forward bending to describe the complete movement strategy. For instance, with the improved SteamVR 2.0 tracking technology, it is possible to use up to four base stations, which combined with the newer and lighter VIVE trackers 3.0, ensure a better coverage of the recording area and more precise measurements. Another viable solution might be the use of a laser metre firmly fixed to the fingers of the participants.

Another limitation in our measurements is that we only recorded the last repetition of the five forward bends performed by the participants. While it is generally accepted to measure mobility after a steady state is reached, we observed that the gained distances tended to reduce across the different repetitions. This may have led to an underestimation of the immediate impact of the intervention and missed the opportunity to observe the progressive decrement of the distance gain, probably resulting from a violation of the new expectancy induced by the visual-haptic illusion. By adopting more objective and automatic measurements, it would have been possible to conduct multiple assessment within the different time periods. This solution would have provided deeper insights into how the exposure to a multisensory context, as the one proposed in our study, influences participants' strategy to reduce the fingertips to floor distance.

As mentioned above, we analysed a small sample size, typical of exploratory studies whose aim is to test feasibility rather than interventions' efficacy. By examining the effect sizes and their 95% CI obtained in the between group comparisons of the distance gains, we can speculate a trend towards the improvement of the effects in favour of the G + group compared to the G0, and in favour of the G ++ group compared to the G + group. Therefore, a larger sample size might exalt the difference between our experimental conditions globally, improving the interpretation and relevance of the results.

In our work we did not objectively analyse the evolution of participants' expectations, limiting to asking whether the participants had become aware of the visual-haptic illusion during the course of the experiment. This can be a starting point for future research aimed at studying more deeply the actual correlation between expectations and motor performance. Quick and easy to administer questionnaires (such as Likert scales) can be integrated into the virtual scenario giving the participant the opportunity to express on-the-go their expectations regarding the effectiveness of the sham manoeuvre⁶⁴.

Another limitation of our study is the use of a convenience method to allocate participants in each group. Participants were assigned to specific groups based on their order of arrival, without implementing a structured randomisation process. However, the descriptive analysis of the population did not show significant differences between the groups. In this regard, one factor we did not consider is the participants' initial level of athletic ability and mobility, which could explain the group differences in fingertip-to-floor distances over time and might have influenced the degree of the effect of the different interventions. Future research should assess these factors as potential covariates.

As a final remark, our preliminary investigation did not consider an additional condition where participants should experience the visual-haptic illusion after receiving a neutral statement regarding the efficacy of the sham manoeuvre. This would have helped to understand better the reason behind the differences observed between the three groups.

Our findings represent a promising initial step in exploring the potential of IVR-based interventions to create multisensory contexts that promote positive movement-related expectations and improve motor outcomes.

In this regard, in line with recent literature³², our experimental protocol based on the forward bending task represents an innovative approach that could be particularly valuable for treating chronic low back pain, where negative mindset and fear-avoidance beliefs, are contributing factors of kinesophobia, and reduced mobility³⁷. Thus, future studies should improve and test our paradigm in a larger sample and in people with restriction in forward bending due to disease-related conditions (e.g., low back pain).

Data availability

The CONSORT checklist, the data supporting the findings of this study and the Python statistical analysis script are included in the Supplementary Data file. The software of the virtual simulation is available from the corresponding author upon reasonable request.

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Author contributions

MT conceived the study and its protocol; MJ developed the VR scenario. MM, LGS, AV and MJ coordinated the planning, recruitment, and experimental sessions. All authors participated in the analysis and interpretation of the results and contributed to the writing and revision of the final manuscript.

Declarations

Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Additional information

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