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RESEARCH ARTICLE

Congruent Kinesthetic and Tactile Haptic Rendering Accelerates the Learning of Highly Dynamic Virtual Sensorimotor Tasks

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ABSTRACT Advances in haptic technologies enable rich, multi-channel haptic rendering of interactions with virtual objects during virtual reality training. However, it remains an open question whether multi-channel haptic rendering (kinesthetic and tactile) provides superior motor learning and transfer when training dynamic tasks compared to simpler, single-channel sensory information. We investigated how 40 participants learned to invert and balance a virtual pendulum after training under four haptic rendering conditions: congruent kinesthetic and tactile rendering, kinesthetic rendering alone, tactile rendering alone, and no haptic rendering. Kinesthetic information was delivered through a delta robot, and tactile information through a two-dimensional skin-stretch device at the finger pads. Participant performance was measured in catch trials during training, in short- and long-term retention trials, and with a transfer task with a shorter pendulum. Participants from all four training conditions demonstrated the ability to improve and transfer their skills. However, we observed poorer performance during catch trials when training with reduced or absent haptic rendering compared to training with congruent kinesthetic and tactile rendering. The advantage of congruent haptic rendering over conditions lacking kinesthetic rendering was maintained during short-term retention, whereas no significant performance differences were observed between conditions in long-term retention and the transfer task. These results suggest that congruent haptic rendering benefits the task's early learning by supporting the generation of internal models of the task dynamics, with kinesthetic rendering playing a major role. Overall, our findings highlight the potential benefits of multi-channel haptic rendering to accelerate virtual reality training.

INDEX TERMS Haptic rendering, kinesthetic information, motor learning, skin stretch, tactile information, virtual reality training.

I. INTRODUCTION

There is growing interest in designing haptic devices that simulate the interaction forces with tangible virtual objects and environments during virtual reality (VR) training. Applications include robot-aided neurorehabilitation for individuals with acquired brain injuries [1], [2], as well as industrial skills training [3] and surgical education [4]. Haptic devices can provide somatosensory input through multiple channels, e.g., through kinesthetic and tactile mechanoreceptors located in our muscles and tendons, or skin, respectively. Importantly, it has been shown that such somatosensory information is essential for fine motor control [5], [6] and the generation of internal models [7],

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which contribute to effective motor learning. Here, we refer to motor learning as relatively permanent, long-term changes in capability for skilled movement, or habit, following practice or experience [8]. Yet, the effectiveness of haptic rendering of virtual objects' dynamics on motor learning and skill transfer remains generally understudied.

A. RELATED WORK

Several studies have shown that integrating haptic rendering into VR training environments enhances task performance when compared to providing visual information alone, e.g., in discriminating size and stiffness of virtual objects [9] (14% to 25% improved mean response times) or improving completion times in a peg-insertion task [10] (30% to 34% improved mean task completion time). A few motor learning studies have also incorporated haptic rendering into their protocols to provide a more ecologically valid virtual training environment. These motor learning studies typically evaluate the effect of different haptic training strategies, such as providing robotic assistance, on learning tasks that incorporate a dynamic system, e.g., controlling a mass with a joystick through a rendered virtual spring-damper connection [11] or controlling a virtual pendulum whose dynamics are rendered through an end-effector device [12], [13]. Haptic rendering has also been leveraged to increase the variability of practice, e.g., by altering the viscosity of the rendered water during rowing training in a robotic simulator [14], and therefore promote motor learning, in line with the contextual interference literature [15].

More recently, Özen et al. showed the benefits of kinesthetic haptic rendering when learning to interact with virtual objects with complex dynamics, namely inverting a simple pendulum [16]. They found that kinesthetic haptic rendering of the pendulum dynamics indeed enhances motor learning and skill transfer compared to no haptic rendering. This is in line with the specificity of practice hypothesis, which states that motor learning is maximized when the training conditions closely match the conditions of the task to be learned [17]. With current advances in haptic technology, such as new tactile displays, it is now possible to achieve even greater fidelity in the haptic rendering of tangible virtual objects (see [18], [19], [20] for reviews). Recent studies have shown that congruent kinesthetic and tactile haptic rendering is beneficial for the perception of virtual object shapes and weights [21], [22], compared to haptic rendering through a single modality. Here, we use the term *congruent rendering* to denote haptic stimuli that are derived from the same simulated interaction and are consistent in time and space [23]. However, it is an open question to what extent the richness of the sensory information—e.g., the provision of multi-channel haptic information (kinesthetic and tactile) versus single-channel sensory cues—influences motor learning and transfer in highly dynamic tasks.

The central nervous system combines and integrates information from multiple sensory modalities in a statistically optimal manner, weighting each input by its reliability to reduce perceptual uncertainty [24]. Thus, removing one of the haptic channels reduces the available sensory information and may increase uncertainty in the learner's internal estimates of movement dynamics, potentially leading to less stable motor representations. Furthermore, research on multisensory learning has shown that redundant, congruent inputs across modalities can enhance both perceptual learning and memory consolidation [23], suggesting that disrupting this redundancy by removing kinesthetic or tactile rendering could hamper the acquisition and retention of complex motor skills.

B. STUDY OBJECTIVE AND HYPOTHESES

In this parallel-design study with forty participants, we compared the effects of training with different modalities of haptic rendering—namely, congruent kinesthetic and tactile rendering (HR), tactile only (TR), kinesthetic only (KR), and no haptic rendering (NR)—on learning to invert a virtual pendulum and transferring the acquired skill to a shorter pendulum. The haptic rendering of the pendulum dynamics was delivered through a delta-robotic base that could provide kinesthetic information to the participant's right hand, and a hand module with a novel two-dimensional skin-stretch device capable of rendering tactile information to the finger pads, collectively from the index to the little finger.

We evaluated learning as the capability to invert the pendulum, whose dynamics were rendered through congruent kinesthetic and tactile information, as it most closely approximates real-world interactions. The participants' task performance was assessed in catch trials during training and in retention trials shortly after training. Motor learning was evaluated in long-term retention trials after 1 to 3 days. We also assessed the participants' perceived mental, physical, and temporal demands, as well as their performance, effort, and frustration, after the short-term retention test using the Raw Task Load Index (RTLX) questionnaire [25]. These factors were evaluated as they may affect the participants' learning capacities; for example, high mental and temporal demand may overload participants and hinder their learning capacity [26], [27], and high physical effort could lead to muscular fatigue, thus hindering performance [8].

Based on the specificity hypothesis [17] and the principles of sensory integration [24], we formulate the following hypotheses:

H1 Participants training with HR will achieve higher performance during training (catch trials) than participants training with KR, TR, or NR.

H2 Participants trained with HR will exhibit greater improvements in performance in the main pendulum task from baseline to short- and long-term retention than participants trained with KR, TR, or NR.

H3 Participants trained with HR will exhibit greater short- and long-term improvements in task transfer, i.e., inverting a pendulum with shorter length, than participants trained with KR, TR, or NR.

H4 Based on the findings by Özen et al. [16], we expect higher self-reported physical demand and effort in participants trained with kinesthetic rendering (HR and KR) than those trained without (TR and NR), as they need to deal with the forces from the pendulum dynamics. We do not expect differences between training conditions in perceived mental and temporal demands, or in perceived performance or frustration.

II. METHODS

A. PARTICIPANTS

We recruited 41 healthy right-handed adults from the students and staff members of TU Delft to participate in the study (18 female, 23 male, ages 22–35 years). The study was approved by the TU Delft Human Research Ethics Committee (HREC; approval number 5981) and adhered to the ethical standards outlined in the Declaration of Helsinki [28].

B. THE PENDULUM GAME

The task to be learned consisted of inverting a virtual pendulum (Fig. 1) and keeping it upright as long as possible. A video demonstrating the task can be found in the Supplementary Material. The virtual pendulum was modeled using its dynamic equations, as in [12] and [29]. It had one internal degree of freedom, its angle θ, with $\theta = 0$ at its resting position. The participants could manipulate the pendulum by translating its pivot point, using the hand module mounted on the delta-robotic base (Fig. 2a; Section II-D). Translation movements were allowed in directions parallel to the participants' frontal plane, i.e., in the y/z-plane of the delta device (Fig. 1a).

The equation of motion of the pendulum is as follows:

$$\ddot{\theta} = -\frac{1}{l}\left((\ddot{z} + g_{\lambda})\sin\theta + \ddot{y}\cos\theta\right) - \frac{c}{ml^2}\dot{\theta} \ . \tag{1}$$

The pendulum's mass m was set to 0.35 kg and its rod length l to 0.35 m (0.25 m for the transfer task, see Section II-C). To reduce fatigue and promote the perception of horizontal forces, the gravitational acceleration was set to $g_{\lambda} = 4.9\,\mathrm{m/s^2}$, i.e., half of Earth's gravity. Finally, the damping coefficient $c = 0.0075\,\mathrm{Ns/rad}$ stabilized the pendulum movement while keeping the task challenging.

The forces acting along the pendulum rod are, therefore:

$$F_{\lambda,rod} = m\left((\ddot{z} + g_{\lambda})\cos\theta - \ddot{y}\sin\theta + \dot{\theta}^2 l\right) \ . \tag{2}$$

These forces were applied by the delta robot in the y/z-plane to the participants' hands, and/or by the skin stretch display in the y_s/z_s-plane to the participants' finger pads (see Fig. 2 and Section II-D). We refer to congruent haptic rendering when we simultaneously apply the forces from the pendulum dynamics to both devices, the delta robot and the skin display.

The pendulum game was displayed on a standard computer screen. The space-themed visualization was intended to provide a visually engaging experience and a rationale for the atypical gravitational acceleration. Participants could move their hand within the workspace of the delta-robotic base in the y/z-plane. The physical limits of this workspace were represented by an elliptical viewport of a spaceship modeled in the virtual environment. A simple virtual representation of the participant's hand was placed around the pivot point of the pendulum to contextualize the perceived haptic information. The pendulum game was modeled in Unity (version 6000.1.13f1, Unity Technologies, USA), running at 90 frames per second.

To provide participants with concurrent visual feedback about their performance, we displayed a score, calculated based on the normalized distance between the pendulum's internal degree of freedom and the desired upright position ($\theta = \pi$), computed at each timestep i as:

$$\hat{\theta}_i = 1 - \frac{|(|\theta_i| \mod 2\pi) - \pi|}{\pi}. \tag{3}$$

These values were then accumulated over the previous time steps of the current trial and normalized over the total duration of each trial ($t_{trial} = 40\,\mathrm{s}$), yielding the participants' score at timestep i:

$$\mathrm{score}_i = 100 \cdot \sum_{i=0}^{\frac{t_{trial}}{\Delta t}} \frac{\hat{\theta}_i \cdot \Delta t}{t_{trial}}. \tag{4}$$

Here, $\Delta t = 0.001\,\mathrm{s}$ denotes the duration of each timestep i of the control loop. Thus, the final score participants could obtain per trial ranged from 0 to 100, with 100 being a perfect performance. Participants could see their remaining trial time, current score, and high score—i.e., the highest total trial score achieved during the ongoing session—at all times on the screen.

C. EXPERIMENTAL PROTOCOL

The experiment consisted of two sessions, scheduled 1 to 3 days apart. The first session took approximately 60 minutes, while the second lasted 10 minutes. Participants were randomly assigned to one of four groups, each trained under a different haptic rendering condition: full haptic rendering with congruent kinesthetic and tactile rendering (HR), kinesthetic-only rendering (KR), tactile-only rendering (TR), and no haptic rendering (NR).

At the start of the first session, participants provided information about their age and sex, and their hand size was measured. Their right-handedness was confirmed using the Edinburgh Handedness Inventory (EHI) [30]. Then, the experimenter read aloud the task instructions and task goal. Participants were also informed about how to interpret the score they received while performing the task (Section II-B) and were instructed to strive for the highest score possible. In addition to the verbal instructions, participants were shown a video demonstrating the task (see Supplementary Material).

After this initial introduction, participants were invited to sit in front of a computer screen, and their right hands were donned in the hand module, which was adjusted

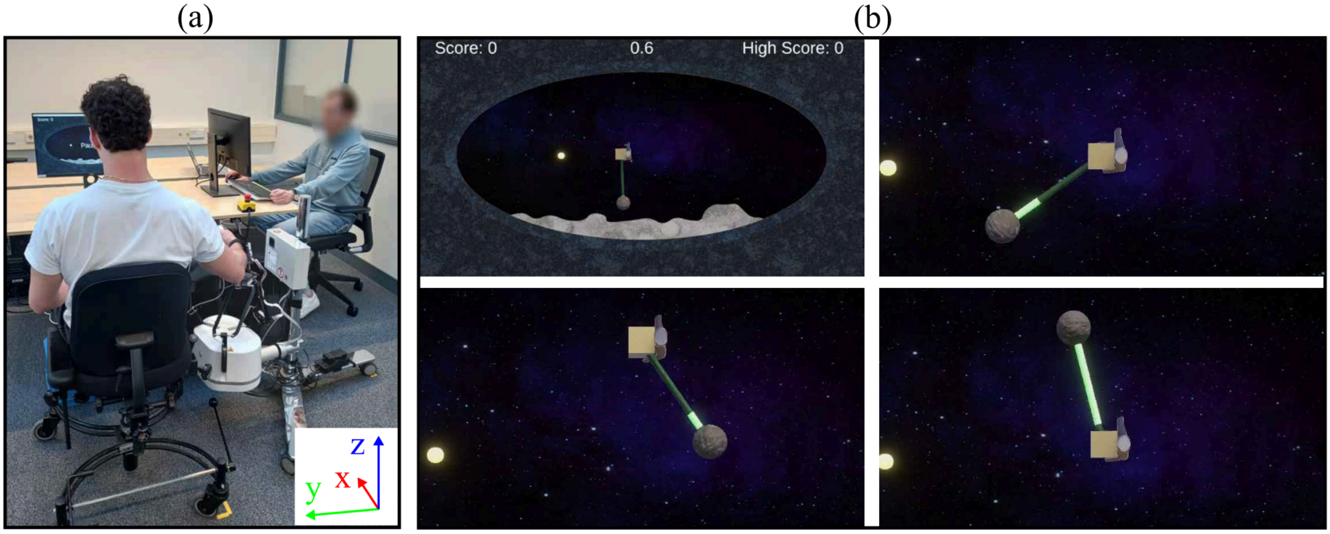

FIGURE 1. (a) Experimental setup with a participant seated, looking at the pendulum game on the computer screen, and with their right hand donned in the hand module. The participant is wearing in-ear headphones (not visible), and the experimenter sits to the right of the participant. Depicted is the coordinate system of the delta-robotic base. (b) The pendulum game. The pendulum has a round mass and a square pivot point, held by a small virtual hand. The game is shown in different stages, with the pendulum in the resting position ($\theta = 0$, top left; full-screen), swinging (top right, bottom left; close-up), and inverted ($\theta \approx \pi$, bottom right; close-up). The bright segment of the pendulum rod increases as the pendulum gets closer to being upright, as an additional visual indicator for good momentary performance. The score, time elapsed in the specific trial, and high score are shown at the top of the screen. The elliptical viewport aims to represent the physical workspace of the delta-robotic base in the y/z-plane.

to the participants' hand sizes by installing one of four available handle sizes [31]. Participants were also equipped with noise-cancelling headphones (WF-1000XM4, Sony, Japan; W830NB, Edifier, China), playing white noise to prevent the sound from the haptic devices from influencing their performance. Participants were offered the in-ear headphones first (WF-1000XM4), and if they did not fit or were uncomfortable, they were provided with the over-ear alternative (W830NB). The complete experimental setup is shown in Fig. 1a.

The experimental protocol is depicted in Fig. 3. It consists of 45 trials in total, each lasting 40 s, where participants attempt to invert the pendulum and maintain the inverted position, with an additional 5 s countdown preceding each trial. Between trials, participants were allowed to rest to reduce potential fatigue. The first familiarization trial (F) was designed to help participants become familiar with the task and ensure they understood what was expected of them. This was followed by 2 baseline trials (BL) to assess their initial task performance. Next, participants performed 2 transfer baseline trials (TBL) with a pendulum with a shorter rod length (see Section II-B). These served as a baseline to assess skill transfer to an altered pendulum dynamics. During these initial familiarization and baseline trials, participants performed the task under the HR condition, as we considered this the closest possible to the information experienced when manipulating a real pendulum.

Following the initial baseline trials, the actual training, consisting of 30 trials, started. In 25 trials, participants trained the task under the condition to which they were allocated, i.e., HR, KR, TR, or NR. The other 5 trials were catch trials (CT), which consisted of practicing the task with HR, as during baseline and retention. The catch trials were irregularly spaced according to a fixed schedule to avoid participants anticipating their appearance (Fig. 3). They were intended to measure the progression of the participants' performance with HR during training.

After a mandatory break of at least 2 minutes, the session continued with 1 washout trial (WO), consisting of performing the task with HR and the non-shortened pendulum. The WO trial was included to allow participants to re-familiarize themselves with the HR condition before retention was assessed, thereby washing out potential carry-over effects from the training condition. The washout was followed immediately by 2 short-term retention trials (STR) and 2 transfer short-term retention trials (TSTR) to assess participants' short-term learning of the main and transfer tasks, respectively. These trials were an exact replica of the (transfer) baseline trials at the start of the experiment, i.e., participants performed the STR and TSTR trials with HR, and the pendulum rod was shortened for the TSTR trials.

After the TSTR trials, participants were asked to complete a questionnaire on their perceived mental and physical workload with the Raw Task Load Index (RTLX) [25]. Furthermore, participants were asked to report any adverse events and share their experience with the haptic devices and pendulum game in writing. The complete questionnaire is provided in the Supplementary Material.

Participants were then invited to a second session, held 1 to 3 days after the first one, to evaluate motor learning. This session started with 1 warm-up trial (WU), where

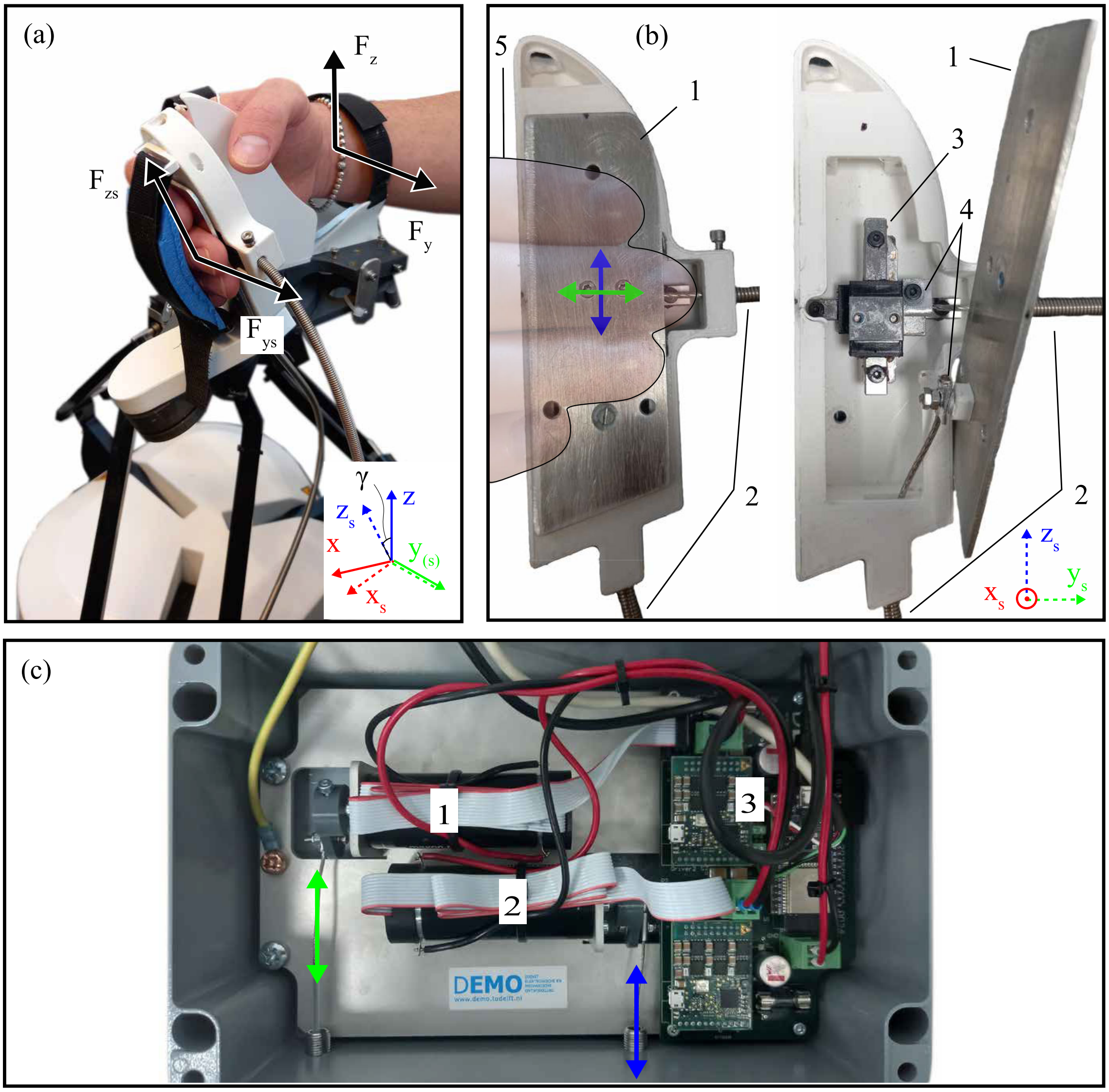

FIGURE 2. **(a) Close-up view of a participant's hand and the haptic devices, composed of the delta-robotic base, the hand module, and the skin stretch display. The back of the fingers is supported by a padded Velcro® strap. The coordinate system of the skin stretch display (x_s, y_s, and z_s) is rotated by $\gamma = 20^\circ$ around the y-axis of the coordinate system of the delta-robotic base. The black arrows indicate the tactile forces acting on the fingertips (F_{ys}, F_{zs}) and the kinesthetic forces acting on the hand and arm (F_y, F_z). (b) Isolated view of the skin stretch display. On the right side, the device is partially disassembled to show its mechanism. (1) Aluminum platform for contact with the participant's finger pads. The blue and green arrows symbolize the pushing and pulling of the Bowden cables on the platform in two dimensions. (2) Bowden cables connecting the platform and positioning stage to the actuation system. (3) 2-DoF positioning stage with two perpendicularly stacked linear rails, connected by a steel bracket. (4) Aluminum clamps connecting the Bowden cables to the bracket and platform, respectively. (5) Illustration of the user's fingertips positioned on the platform. (c) Actuation module of the skin stretch display with the two motors (1, 2) connected to the Bowden cables via levers, and (3) motor drivers and microcontroller. The blue and green arrows indicate the pushing and pulling of the Bowden cables, corresponding to the blue and green arrows in (b).**

participants performed the main pendulum task with HR to re-familiarize themselves with the setup. Right after the warm-up, participants performed 2 long-term retention (LTR) trials and 2 transfer long-term retention (TLTR) trials, which followed the same exact structure as the STR and TSTR trials.

D. HAPTIC DEVICES

1) KINESTHETIC HAPTIC DEVICE

The employed kinesthetic haptic device is based on a three-degree-of-freedom (3-DoF) delta robot (Lambda.3, Force Dimension, Switzerland), which can provide translational forces to the hand of up to 20 N in a workspace of $\varnothing$ 220 × 170 mm^2. We included a custom-made hand module at the robot end-effector, a modification of the palmar device PRIDE from Rätz et al. in [31] and [32] (Fig. 2a). While PRIDE allows for natural flexion and extension of the collective movement of index to little fingers, we physically fixed the angle to 90° for the duration of the study, as the additional DoF was not required to perform the task.

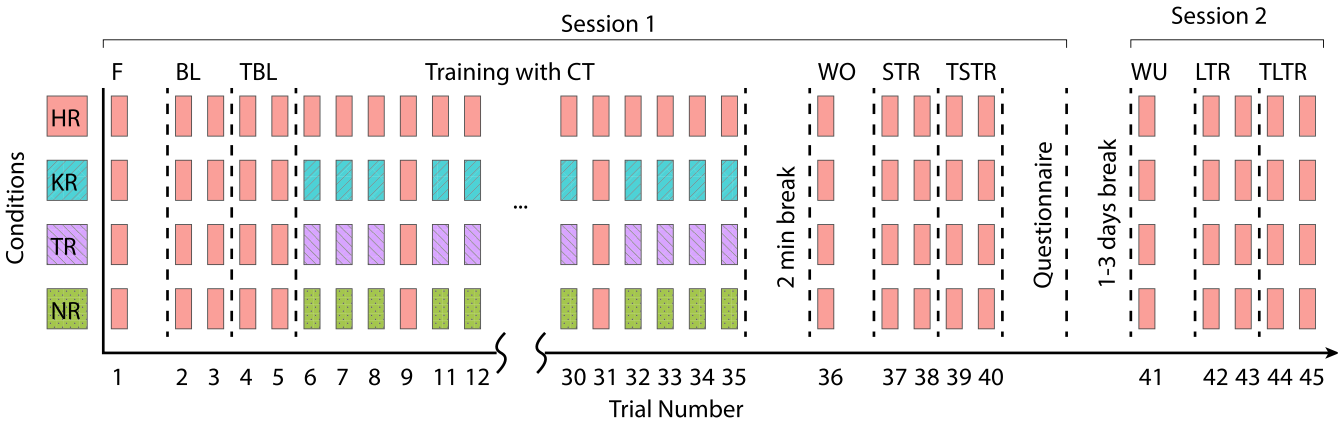

FIGURE 3. **Experimental Protocol. The four training conditions are depicted with different colors and fill patterns: congruent kinesthetic and tactile rendering (HR), kinesthetic rendering only (KR), tactile rendering only (TR), and no haptic rendering (NR). Each rectangle symbolizes a trial of 40 s, initiated by a 5 s countdown. Participants were allowed to rest freely between trials. HR was the default condition for all trials, except for the indicated training trials. The different trials are abbreviated as: familiarization (F), baseline (BL), transfer baseline (TBL), catch trial (CT), washout (WO), short-term retention (STR), transfer short-term retention (TSTR), warm-up (WU), long-term retention (LTR), and transfer long-term retention (TLTR).**

2) TACTILE HAPTIC DEVICE

We augmented the PRIDE hand module with a novel 2-DoF multi-finger skin stretch device to provide tactile stimulation. The novel skin stretch display replaces the end-effector of the hand module at the point where the fingertips and the hand module are in contact (Fig. 2a–b). The fingertips are therefore in contact with a platform mounted to two shortened miniature linear rails (SSEB6-70, MISUMI, Japan) with $10 \times 10\,\text{mm}^2$ of travel. The rails are stacked on top of each other, rotated by 90° to allow for smooth 2-DoF movements lateral to the fingerpad. Note that the tactile display aligns with the handle's longitudinal axis, i.e., the orientation of a straight line connecting the centers of the fingertips of the index and little fingers. To achieve a natural cylindrical grasp, this longitudinal axis is rotated by $\gamma = 20°$ around the y-axis of the coordinate frame of the delta-robotic base [32], resulting in the coordinate system of the skin stretch display ($\mathrm{x_s}$, $\mathrm{y_s}$, and $\mathrm{z_s}$) illustrated in Fig. 2a–b.

The platform is remotely actuated by two 60 W DC motors (268216, Maxon Motor AG, Switzerland) via two levers (18 mm lever arm) connected to Bowden cables (unbranded, 1.5 mm braided steel wire, polytetrafluoroethylene inner sleeve, 5 mm wound steel outer sleeve) with lengths 75 cm and 100 cm for the $\mathrm{y_s}$ and $\mathrm{z_s}$ axes, respectively. The remote actuation enables the system to be lightweight at the end-effector, providing a backdrivable direct-drive system.

The motors are controlled with two drivers (Escon 70/10, Maxon Motor AG, Switzerland) in current-control mode and a microcontroller (ESP32 DEVKIT V1, Espressif, China), and powered by a 48 V power supply (QS40.481, PULS GmbH, Germany). The remote actuation system, i.e., the motors, drivers, microcontroller, and power supply, is housed separately and connects to the hand module via the Bowden cables (Fig. 2c).

E. HAPTIC DEVICE CONTROL

The control of the haptic devices was implemented in C++ (C++20) with a control loop frequency of 1 kHz. The Lambda.3 was controlled using the Software Development Kit (SDK, Force Dimension; version 3.15.0). The SDK enabled reading the end-effector position, applying forces in tool space, and compensating for the weight of the hand module.

The forces from the pendulum dynamics, calculated using eq. 2, were rendered at the Lambda.3 end-effector (kinesthetic haptic rendering). The end-effector acceleration employed in eq. 2 was obtained by backward differentiation of the position signal, and subsequently filtered with a fourth-order Butterworth filter at 40 Hz to ensure system stability. Using the filtered acceleration and eq. 1, the pendulum's angular acceleration $\ddot{\theta}$ was computed and integrated to obtain the angular velocity $\dot{\theta}$ and angle θ. From these values, the pendulum interaction forces were determined and rendered to the participant via both the robotic base and the skin stretch display. We did not account for the rotational offset between the skin stretch and Lambda.3 coordinate frames, and displayed the same force magnitudes in the y/z and $\mathrm{y_s}/\mathrm{z_s}$ planes.

The skin stretch display was feedforward force controlled, with a force rendering accuracy of 88.8%, maximum forces of ±4 N, and an effective bandwidth of up to 10 Hz in both axes. The display received command currents at 200 Hz through a serial connection. These commanded currents were obtained through a model that maps the desired forces to currents, individually for each axis j:

$$I_j(F_j, \dot{F}_j) = \frac{F_j - b_j - c_j \tanh(\beta \dot{F}_j)}{a_j}. \tag{5}$$

Here, F_j and $\dot{F}_j$ are, respectively, the desired force and its derivative in the j axis, i.e., either in direction $\mathrm{y_s}$ or $\mathrm{z_s}$

(Fig. 2a–b). The scalars a_j and b_j are the slope and offset of the mapping function for each motor and axis, respectively. We added a non-linear term to the model, dependent on the force derivative $\dot{F}_j$, to account for the backlash of the Bowden cables. This term included a gain of c_j and a smoothing factor of $\beta = 2$.

The force derivatives $\dot{F}_j$ were calculated using the backward difference and a fourth-order Butterworth filter with a low-pass of 10 Hz. This allows for smooth behavior with respect to the hysteresis caused by backlash, while preserving the system's bandwidth. The model was fitted on a test bench, yielding $a_{y_s} = 3.2551, a_{z_s} = 3.6705, b_{y_s} = -0.3090, b_{z_s} = -0.1784, c_{y_s} = -0.6918, c_{z_s} = -0.7208$. Detailed information on the modeling and characterization procedure of the skin stretch device is provided in the Supplementary Material. To maintain safe operation, commanded forces were limited to the operating ranges of the devices. Both the control software and the Unity game (Section II-B) were executed on a desktop computer running Ubuntu 22.04.4 LTS with a real-time kernel (5.15.0-1067).

F. OUTCOME METRICS

The primary outcome metric in this study was the score achieved at each trial, as it measured the participants' performance in relation to the goal they were asked to achieve, i.e., to invert the pendulum and maintain its inverted position. Note that the score used in the analysis is divided by 100, yielding a normalized score from 0 to 1, with 1 being perfect performance. Note that a perfect performance of 1 was impossible to attain, as that would require instantaneous pendulum inversion.

The results of the RTLX were used to monitor potential workload differences between conditions. We included the six subscales of the questionnaire, namely perceived mental, physical, and temporal demands, as well as the perceived performance, effort, and frustration. We analyzed the subscales individually, rather than computing an overall workload score, to help localize the source of workload differences [25]. The RTLX scores per subscale ranged from 0 (low) to 20 (high).

The feedback gathered from the participants was used to gain insights into their experiences with the haptic devices and to inform future development of the device; therefore, it is outside the scope of this paper.

G. STATISTICAL ANALYSIS

We evaluated whether training with different haptic rendering approaches affected the participants' ability to invert the pendulum as the training progressed. To this end, we examined the effect of the training condition on the score changes across catch trials, i.e., those training trials when congruent kinesthetic and tactile rendering was provided. We used the following linear mixed-effects model (LMM) for the analysis:

$$\begin{aligned}\text{CT\_score} \sim\ & \text{condition} \times \text{CT\_index} + \text{BL}_{\text{avg}} \\ & + (1 + \text{CT\_index} \mid \text{participant\_id}). \qquad (6)\end{aligned}$$

Here, CT_score represents the score achieved during each of the catch trials and CT_index denotes the catch trial index (0 to 4, where 0 corresponds to the first catch trial). We included the main effect of the initial skill level, measured as the centered mean baseline score per participant (BL_{avg}), to account for differences in initial skill levels between participants. Furthermore, to account for between-participant differences in overall performance and in how performance changed across catch trials, we included random intercepts and random slopes for the catch trial index, grouped by participant.

We also evaluated the effect of training under the four haptic conditions on both short- and long-term score improvements relative to the baseline. We evaluated both learning to invert the pendulum, whose dynamics were employed during training, and the transfer to invert a pendulum with different dynamics. To that end, we formulated the following model:

$$\begin{aligned}\text{score} \sim\ & \text{condition} \times \text{test\_trial} \\ & + (1 + \text{test\_trial} \mid \text{participant\_id}). \qquad (7)\end{aligned}$$

Here, score denotes either the baseline and retention scores of the main task (BL, STR, and LTR) or the transfer task (TBL, TSTR, and TLTR). The test_trial is a variable that defines whether the score was obtained in a baseline, short- or long-term retention trial.

To assess differences in subjective task load across conditions, Kruskal-Wallis tests were conducted separately for each of the six RTLX subscales.

The statistical analysis was conducted in R (version 4.4.1). The HR condition was used as the reference level in all LMMs. The first CT was used as reference in the CT_index in eq. 6, while baseline was used as reference in test_trial in eq. 7. Model assumptions of the LMMs—namely, approximate normality of residuals and random effects and homoscedasticity of residuals—were verified through visual inspection of residual and random-effect Q–Q plots, residuals versus fitted plots, and box plots of residuals by participant. For the LMM analyses, confidence intervals (CIs) were estimated with the *confint* function (*profile* method). Furthermore, Cohen's d values were calculated for the relevant reference contrasts in each LMM—condition contrasts in the catch-trial analysis, and condition, test_trial, and condition-by-test_trial contrasts in the retention analyses. The significance level was set at $\alpha < 0.05$ for all tests.

III. RESULTS

Of the 41 recruited participants, 40 successfully completed both sessions and were included in the analysis (18 female, 22 male, ages 22–35 years). The first session of one participant was prematurely terminated as one of the capstan cables of the delta-robotic base snapped. This led to the exclusion of this participant from the study and delayed the second session of another participant by one day. The right-handedness of all participants was confirmed by the

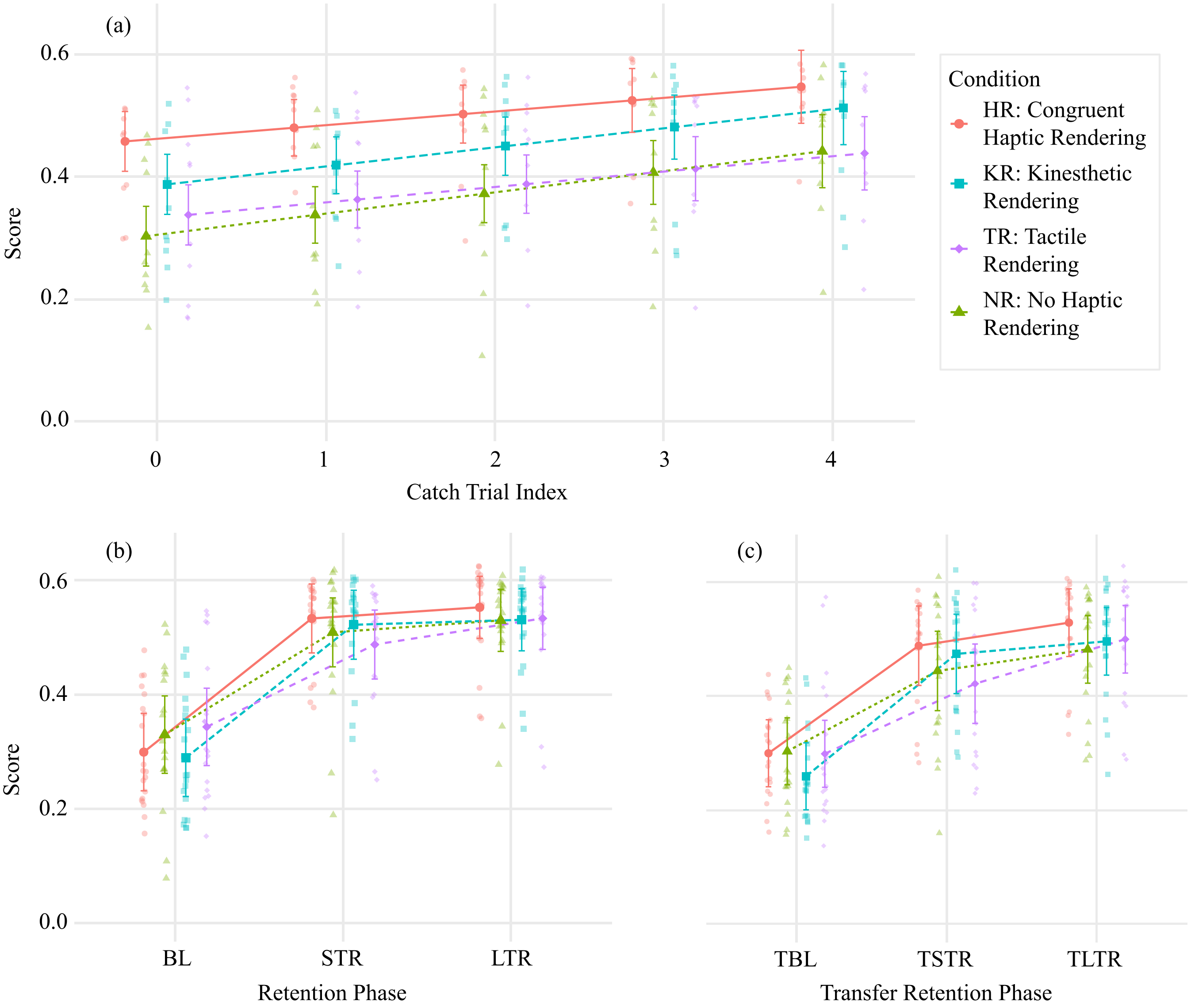

FIGURE 4. (a) Scores participants obtained in the catch trials while training with the four haptic rendering conditions. (b) Scores achieved in the main trained task during baseline (BL), short-term retention (STR), and long-term retention (LTR) in each training condition. (c) Scores obtained in the transfer task with the shortened pendulum during transfer baseline (TBL), transfer short-term retention (TSTR), and transfer long-term retention (TLTR), per training condition. Small markers show individual scores per trial, large markers and lines show LMM-estimated means, and error bars show the corresponding 95% confidence intervals.

EHI. An example of the forces applied to a participant during a single trial is provided in the Supplementary Material.

A. PERFORMANCE DURING TRAINING

Results from the LMM analysis of the catch trials are reported in Table 1 and visualized in Fig. 4a. In general, participants performed significantly worse in the first catch trial (CT_index = 0 in Fig. 4a) when they trained under conditions that lacked haptic rendering or only provided tactile or kinesthetic rendering, compared to those trained with congruent kinesthetic and tactile rendering.

We found a significant increase in the score as the training progressed, i.e., a significant main effect of the catch trial index. We did not, however, find significant differences in the score increase as training progresses between any of the partial (or no) haptic rendering conditions and the congruent condition. Finally, we found that participants with a higher baseline score were associated with higher catch-trial scores, as indicated by the significant main effect of the baseline score.

B. MOTOR LEARNING OF THE MAIN PENDULUM TASK

Results from the LMM analysis of the performance improvement from baseline to short- and long-term retention in the main task (eq. 7 with BL, STR, and LTR scores) are reported in Table 2 and visualized in Fig. 4b. The

TABLE 1. Results from the linear mixed-effects model analysis on catch-trial scores. The congruent kinesthetic and tactile rendering condition (HR) is the reference training condition. KR: kinesthetic rendering only, TR: tactile rendering only, NR: no haptic rendering, CT_i: catch-trial index, BL_{avg}: centered baseline score, SE: standard error, df: degrees of freedom, CI: confidence intervals, and d: Cohen's d for condition contrasts against HR at CT_i = 0 and $BL_{avg} = 0$. Significant p-values are highlighted in bold.

Effect	Estimate	SE	df	t	p	95% CI	d
Intercept	0.457	0.024	34.9	19.02	< **.001**	[0.412, 0.503]	
KR	-0.070	0.034	34.9	-2.07	**.0462**	[-0.134, -0.006]	-1.64
TR	-0.120	0.034	35.1	-3.50	**.0013**	[-0.184, -0.055]	-2.81
NR	-0.155	0.034	35.0	-4.54	< **.001**	[-0.219, -0.091]	-3.63
CT_i	0.022	0.007	36.0	3.35	**.0019**	[0.0096, 0.0350]	
BL_{avg}	0.681	0.113	35.0	6.03	< **.001**	[0.464, 0.898]	
KR:CT_i	0.009	0.009	36.0	0.94	.354	[-0.0091, 0.0268]	
TR:CT_i	0.003	0.009	36.0	0.30	.765	[-0.0151, 0.0208]	
NR:CT_i	0.012	0.009	36.0	1.32	.196	[-0.0055, 0.0303]	

TABLE 2. Results from the linear mixed-effects analysis on baseline (BL), short- (STR), and long-term retention (LTR) scores of the main task. Congruent kinesthetic and tactile rendering (HR) and baseline are treated as reference. KR: kinesthetic rendering only, TR: tactile rendering only, NR: no haptic rendering, SE: standard error, df: degrees of freedom, CI: confidence intervals, and d: Cohen's d for contrasts against HR. Significant p-values are highlighted in bold.

Effect	Estimate	SE	df	t	p	95% CI	d
Intercept	0.299	0.033	36.0	8.95	< **.001**	[0.235, 0.362]	
KR	-0.010	0.047	36.0	-0.21	.833	[-0.100, 0.080]	-0.11
TR	0.044	0.047	36.0	0.93	.357	[-0.046, 0.134]	0.41
NR	0.031	0.047	36.0	0.65	.521	[-0.059, 0.121]	0.30
STR	0.234	0.026	36.0	8.86	< **.001**	[0.184, 0.284]	3.52
LTR	0.253	0.027	36.0	9.30	< **.001**	[0.201, 0.305]	3.08
KR:STR	-0.001	0.037	36.0	-0.03	.979	[-0.072, 0.070]	-0.01
TR:STR	-0.090	0.037	36.0	-2.41	**.021**	[-0.161, -0.019]	-1.32
NR:STR	-0.055	0.037	36.0	-1.47	.150	[-0.126, 0.016]	-0.73
KR:LTR	-0.012	0.039	36.0	-0.31	.760	[-0.085, 0.062]	-0.13
TR:LTR	-0.064	0.039	36.0	-1.65	.108	[-0.137, 0.010]	-0.77
NR:LTR	-0.054	0.039	36.0	-1.39	.174	[-0.127, 0.020]	-0.68

first important finding is that we did not find significant differences between HR and the other training conditions at baseline. In general, participants showed a significant improvement in their scores from baseline to both retention phases. Those trained with HR seemed to improve their score by a greater amount than those trained with partial rendering, especially those trained with tactile only or no rendering at all. Yet, the difference only reached significance in the increase in score from baseline to STR between the HR and TR conditions.

C. EFFECT OF THE TRAINING CONDITIONS ON TRANSFER

Results from the LMM analysis of the performance improvements in the transfer task, i.e., from transfer baseline to transfer short- and long-term retention (eq. 7 with TBL, TSTR, and TLTR scores) are reported in Table 3 and shown in Fig. 4c. We did not find significant differences between HR and the other training conditions at the transfer baseline. Overall, participant scores significantly improved from TBL to both retention phases. We did not find significant differences in score improvements from TBL to the transfer retention phases between participants who trained with HR and those who trained with the other training conditions.

TABLE 3. Results from the linear mixed-effects analysis on baseline (TBL), short- (TSTR), and long-term retention (TLTR) scores of the transfer task. Congruent kinesthetic and tactile rendering (HR) and transfer baseline are treated as the references. KR: kinesthetic rendering only, TR: tactile rendering only, NR: no haptic rendering, SE: standard error, df: degrees of freedom, CI: confidence intervals, and d: Cohen's d for contrasts against HR. Significant p-values are highlighted in bold.

Effect	Estimate	SE	df	t	p	95% CI	d
Intercept	0.299	0.029	36.0	10.33	< **.001**	[0.244, 0.354]	
KR	-0.040	0.041	36.0	-0.99	.330	[-0.118, 0.038]	-0.56
TR	-0.001	0.041	36.0	-0.02	.981	[-0.079, 0.077]	-0.01
NR	0.003	0.041	36.0	0.08	.934	[-0.075, 0.081]	0.04
TSTR	0.189	0.029	36.2	6.46	< **.001**	[0.133, 0.244]	2.84
TLTR	0.229	0.029	36.1	7.82	< **.001**	[0.173, 0.285]	3.57
KR:TSTR	0.026	0.041	36.2	0.63	.531	[-0.053, 0.105]	0.28
TR:TSTR	-0.066	0.041	36.2	-1.59	.121	[-0.144, 0.013]	-0.75
NR:TSTR	-0.048	0.041	36.2	-1.15	.256	[-0.126, 0.031]	-0.66
KR:TLTR	0.008	0.041	36.1	0.19	.854	[-0.071, 0.087]	0.08
TR:TLTR	-0.028	0.041	36.1	-0.68	.501	[-0.107, 0.051]	-0.32
NR:TLTR	-0.050	0.041	36.1	-1.21	.233	[-0.129, 0.029]	-0.70

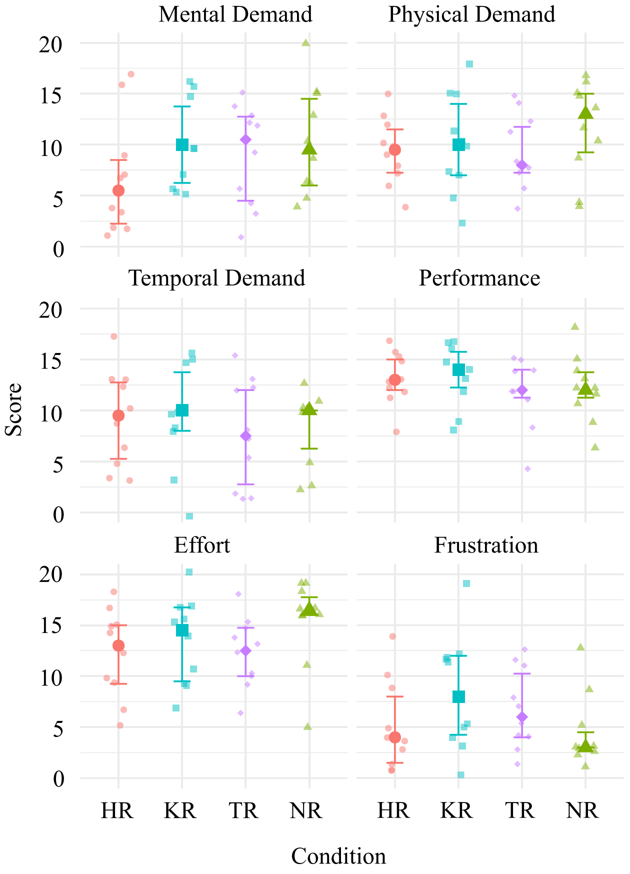

FIGURE 5. Results of the RTLX subscale scores by training conditions: congruent kinesthetic and tactile haptic rendering (HR), kinesthetic rendering (KR), tactile rendering (TR), and no haptic rendering (NR). Small markers indicate individual results, large markers medians, and error bars the inter-quartile ranges.

D. RAW TASK LOAD INDEX

The RTLX results are presented in Fig. 5 by training condition and questionnaire subscales. The Kruskal-Wallis test revealed no significant differences in scores between the conditions per subscale (Table 4).

TABLE 4. Kruskal-Wallis tests for differences in RTLX subscale scores across conditions. Abbreviations: total sample size (*n*), Kruskal-Wallis test statistic (H), degrees of freedom (df), and *p*-value (*p*).

Dimension	*n*	H	df	*p*
Mental Demand	40	3.005	3	0.391
Physical Demand	40	2.105	3	0.551
Temporal Demand	40	0.785	3	0.853
Performance	40	2.377	3	0.498
Effort	40	5.437	3	0.142
Frustration	40	4.248	3	0.236

IV. DISCUSSION

A. TRAINING WITH CONGRUENT KINESTHETIC AND TACTILE HAPTIC RENDERING ENHANCES PERFORMANCE DURING THE FIRST TRAINING PHASES COMPARED TO PARTIAL AND NO RENDERING

We found that training with congruent kinesthetic and tactile haptic rendering (HR) enhanced task performance during training when compared to training with single-channel haptic rendering (KR, TR) and no haptic rendering (NR), supporting our first hypothesis **H1**. This was especially visible in the comparisons between the congruent haptic rendering and the tactile-only and no haptic rendering conditions, where the estimates in the first catch trial were around twice as large as those from the comparison between the congruent haptic rendering and kinesthetic-only conditions.

The worse catch-trial performance in conditions without kinesthetic rendering might be due to participants adjusting their internal predictions and control policies to conditions with little or no forces from the interaction with the delta robot. The forces applied by the tactile display were localized at the finger pads, whereas those rendered by the delta robot affected the participants' arm movements, thus requiring greater physical effort to overcome. This is in line with the work of Özen et al. [16], who showed that adding kinesthetic haptic rendering significantly increased the participants' physical effort in a similar pendulum task. They also showed that reducing participants' effort through arm weight compensation likely hindered the formation of the internal models required to perform the task unsupported. Accordingly, we expected higher self-reported physical demand and effort at the end of the first session in those conditions trained with kinesthetic rendering. This expectation corresponds to **H4**, which was not supported by our data. The lack of significant differences in this subjective score across conditions may reflect more efficient movement control in those trained with kinesthetic rendering, as supported by their better short-term retention scores.

Nevertheless, we also found a significantly worse performance during the catch trials in those trained with only kinesthetic rendering compared to participants trained with congruent haptic rendering. This suggests that reducing the richness of haptic information might have slowed down the first learning phase. The absence of a second haptic information channel reduces the sensory information available to calibrate sensorimotor internal models of the task dynamics, which in the catch trials included both tactile and kinesthetic information. This interpretation is consistent with principles of sensory integration, whereby combining multiple sensory cues reduces perceptual uncertainty [24]. Similar benefits of congruent kinesthetic and tactile haptic rendering have been reported for the perception of quasistatic dynamic systems: van Beek et al. [22] showed that congruent kinesthetic and tactile haptic rendering improved the perception of virtual object weight compared to single-channel rendering. Similarly, considering motor adaptation to viscous curl fields in a simple reaching task, Rosati et al. [33] showed stronger adaptation to combined kinesthetic and tactile perturbations compared to visual perturbations. Finally, Ratschat et al. [21] found that adding tactile to kinesthetic rendering improved virtual shape reproduction performance compared to kinesthetic rendering alone.

Participants continued improving their performance as training progressed, without a clear advantage from the congruent condition over the others. This observation suggests that the enhanced performance improvement in the congruent haptic rendering group occurred very early in the training. The limited number of catch trials (5 CT trials within 30 training trials) restricts our ability to robustly estimate performance curves, for example, by fitting exponential functions [34], to infer conclusions related to differences in adaptation rates between conditions.

B. TRAINING WITHOUT KINESTHETIC RENDERING MAY HAMPER MOTOR LEARNING

We found that participants across all conditions successfully learned how to invert and balance the virtual pendulum, as evidenced by the increased scores in both short- and long-term retention when compared to baseline. However, contrary to our expectation, training with congruent haptic rendering only showed a short-term advantage over those who trained without kinesthetic rendering and only reached significance when compared to the tactile-only rendering condition. Thus, **H2** was only partially supported. Significant differences across conditions dissipated when evaluating long-term retention.

As discussed above, internal models and associated control policies acquired without kinesthetic rendering may require less physical effort and be based on poorer haptic information about the pendulum dynamics compared to those acquired through training with congruent kinesthetic and tactile rendering. This, as observed in the catch trials during training, may have contributed to the differences in performance improvement from baseline to short-term retention between conditions.

The advantage of training with congruent haptic rendering observed during the first catch trial, as opposed to kinesthetic information only, was not maintained in short-term retention. This suggests that the addition of tactile information on top of kinesthetic information did not provide substantial learning benefits as the training progressed. One potential explanation is that the additional tactile information became redundant as participants gained proficiency in the task. This interpretation aligns with the observations of Sigrist et al. [35], who noted that novices usually benefit most from concurrent multisensory feedback to understand task dynamics, while skilled individuals may find it superfluous or even distracting. The latter is, however, not supported by the scores from the RTLX mental demand and frustration subscales. It should be noted that Sigrist et al. referred to extrinsic or augmented feedback, i.e., information that cannot be explained without external input, whereas our haptic rendering could be categorized as intrinsic feedback.

In surgical education, prior work has reported a similar expertise-dependent pattern for supplementary feedback. Studies using visual [36] and tactile [37] force feedback found that additional feedback improved performance primarily in novices, whereas benefits for expert surgeons were reduced or absent. Consistent with these findings, a recent meta-analysis showed that the performance advantage of haptic feedback in robot-assisted surgery is generally smaller in more experienced users [38]. Applied to the present study, this suggests that participants may have initially benefited from the added tactile rendering while still learning the task dynamics, but that this benefit diminished as they became more proficient and increasingly relied on other available information.

Another reason why tactile information may have become less relevant over time relates to how the task's challenge changes during training. Early on, participants must train to invert the pendulum by accelerating and swinging it, and the resulting tactile stimulation may help them to understand its dynamics. As training progresses, inverting the pendulum may become easier, and the main challenge shifts to keeping it upright. In this second phase, the pendulum moves less, tactile forces are small, and the scarce tactile information about the pendulum's state may offer little additional benefit.

Alternatively, it is possible that participants learned to perform the task during the trials where congruent haptic rendering was provided to all participants, namely the catch trials, washout, short-term retention, and warm-up. This exposure to congruent haptic rendering may have helped overcome the limitations of training without the full sensory information predicted by the specificity hypothesis [17].

Overall, our results partially support our hypothesis, which favors (short-term) motor learning after training with congruent kinesthetic and tactile haptic rendering over only tactile and no haptic rendering. However, we could not find convincing evidence regarding the benefits of adding tactile information on top of kinesthetic information.

C. TRANSFER TO DIFFERENT PENDULUM DYNAMICS OCCURS REGARDLESS OF THE TRAINING CONDITIONS

Our results suggest that, in general, participants were able to transfer the ability they gained to invert and balance the pendulum to a version with a shorter pendulum length. Contrary to our expectation, we did not find any significant advantage of training with congruent haptic rendering over the other training conditions. Thus, **H3** was not supported by our data. This expectation was based on our hypothesis that training without congruent haptic rendering would hamper motor learning. This is in line with the results from Özen et al. [16], who found significantly lower retention performance after training without kinesthetic rendering than with kinesthetic rendering in the main task, and this difference also carried over to the transfer task. However, because participants in our experiment were able to learn the main task under all training conditions, it is perhaps unsurprising that they could also transfer the learned skill to a task with altered pendulum dynamics.

An alternative explanation is that the transfer task we selected was not sufficiently challenging. Shortening the pendulum length reduces its inertia, making it easier to invert but harder to keep inverted [39]. Thus, although the dynamics of the transfer task differ from those of the main task and may require an adjustment in movement strategy, performing well may not have been more challenging overall [40]. Other changes to the task dynamics—such as increasing the gravitational acceleration—might increase the task difficulty more substantially and thereby reveal potential differences in the ability to transfer learned skills between training conditions.

D. PRACTICAL IMPLICATIONS

Our findings may have practical implications for different applications, including robot-aided neurorehabilitation, industrial skills training, and surgical education. In rehabilitation settings, congruent multi-channel haptic rendering may support early motor (re)learning in people with acquired brain injuries, potentially facilitating subsequent practice as therapy progresses. In contrast, for industrial skills training in unimpaired individuals, while the rich multi-sensory information might provide an advantage in enhancing performance during training, the reduced long-term advantage of the addition of tactile rendering suggests that training with kinesthetic information may be sufficient. However, as previously discussed, the benefits of tactile, kinesthetic, or congruent haptic rendering may depend on the task being learned and the experimental setup employed. For instance, in surgical education, tactile information may remain crucial for skilled manipulation, even for experienced users. The relative benefit of each haptic modality should therefore be considered in light of the specific training goals, user population, and available haptic rendering systems. Future work may explore adaptive haptic rendering systems that provide rich multi-channel information during early learning, then reduce or personalize the rendered information as users become more proficient.

E. STUDY LIMITATIONS

Several limitations should be considered in relation to this study. Firstly, our findings should be interpreted in light of the specific task we employed. In the pendulum inversion task, kinesthetic rendering impacts the amount of physical effort participants must exert to perform well [16], whereas tactile rendering primarily provides information about the pendulum dynamics without altering the required effort. It is therefore reasonable that we observed clearer effects on performance when kinesthetic rendering was removed, and weaker or inconclusive effects when tactile rendering was removed. This does not imply that tactile information is unimportant for learning complex tasks; rather, it suggests that in this particular task, kinesthetic rendering had a larger impact on performance than tactile rendering. In other tasks, the relative contribution of each haptic channel may differ.

A second limitation of our study is the difficulty of the chosen task. It is possible that the difficulty of the pendulum task was relatively low, despite the highest score we observed being 0.64. As noted above, achieving a performance of 100% was impossible, as the pendulum had to be inverted from the initial resting position at the beginning of each trial. This may have led participants to learn the task largely during the trials with congruent haptic rendering. This likely reduced the sensitivity of our design to detect differences between training conditions in motor learning and skill transfer.

It should be noted that we did not invest in the visual realism of the game scene (e.g., we used an artificial viewport and no realistic virtual hand) because we were primarily interested in evaluating the benefits of haptic rendering for motor learning. This limits the ecological validity of our training environment. Future work could integrate the haptic rendering system with immersive virtual reality to improve visuomotor congruence and the realism of the interaction, thus enhancing ecological validity.

V. CONCLUSION

In this study, we evaluated the effect of training with congruent kinesthetic and tactile haptic rendering, only tactile or kinesthetic rendering, and no haptic rendering on the performance and learning of a virtual pendulum inversion and balancing task. Overall, our results suggest that haptic rendering, and kinesthetic information in particular, is beneficial for learning a virtual pendulum inversion task. We found evidence that favors multi-channel over single-channel haptic rendering, especially during the initial phases of learning. However, differences between training conditions dissipated in long-term retention. Further research is needed to clarify how different haptic rendering combinations influence motor learning in the long run. Our findings advance the understanding of haptic-mediated motor learning, offering a foundation for the development of more efficient VR-based training for robotic neurorehabilitation, industrial skills, and surgery.

DATA AVAILABILITY

The dataset supporting this work is available on the Zenodo repository. doi:10.5281/zenodo.18184255

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