

Teleoperation of Unmanned Ground Vehicles Using Human Foot-Based Interface

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Abstract—Teleoperation remains an important technology for robotic applications, since many tasks cannot yet be fully replaced by autonomous systems. Consequently, the investigation of new teleoperation concepts remains highly relevant for future applications. Although teleoperation has been studied for several decades, its practical use remains limited in many scenarios, and operator interfaces still offer significant potential for alternatives. Therefore, this paper presents a foot-based teleoperation concept for unmanned ground vehicles. The proposed system uses measured foot orientation to generate longitudinal and lateral vehicle commands, which are mapped to speed and steering inputs. The system is implemented and evaluated using a teleoperated small-scale model vehicle. In this four-operator feasibility pilot, the participant-level descriptive results generally favored joystick control, while all operators successfully completed the task using the foot interface. Because of the small sample and fixed condition order, these results demonstrate technical feasibility of the proposed solution.

Index Terms—Teleoperation, unmanned ground vehicles, shared control, hands-free teleoperation interface, wearable inertial sensor, human–robot interaction, Ackermann steering, RoboRacer, Robot Operating System (ROS2)

I. INTRODUCTION

Teleoperation is an important capability for autonomous and semi-autonomous vehicles and robotic systems in edge-case situations where human intervention is required [1]. In the near future, teleoperation will be the most feasible solution to overcome the limitations of fully autonomous systems [2].

Conventional teleoperation interfaces often rely on steering wheels, joysticks, or game controllers, because these devices provide direct and familiar control inputs. However, alternative interfaces can be useful when the operator's hands are occupied, when the control equipment must remain compact, or when a different interaction concept is required [3], [4].

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Wearable interfaces represent a possible alternative to conventional teleoperation devices. By using motion sensors attached to the human body, operator movements can be converted into control commands without requiring a large mechanical input device [5]. This enables teleoperation setups with hands-free operation, and improves inclusiveness by offering an additional control modality for users for whom conventional hand-operated interfaces are inconvenient or inaccessible. In the presented work, the focus is on a foot-based wearable interface, where measured foot orientation is used to generate longitudinal and lateral control commands for an unmanned ground vehicle.

This work presents the implementation and experimental evaluation of a wearable foot-based teleoperation interface for an Ackermann-steered test vehicle. The main contributions of this work are:

- the design of a wearable foot-based teleoperation interface that maps foot orientation to vehicle speed and steering commands;
- the integration of the interface as a joystick-equivalent input into an existing ROS 2-based RoboRacer vehicle stack;
- a feasibility pilot experiment providing a descriptive within-participant comparison of foot- and hand-based teleoperation.

II. RELATED WORK

A. Teleoperation of Ground Vehicles and Mobile Robots

Remote operation remains a key capability for UGVs and automated road vehicles [1]. Typical teleoperation setups rely on hand-operated devices, including steering wheels, joysticks, and game controllers. While these interfaces provide familiar control mappings, they also constrain the operator to a hand-bound interaction mode and may be less suitable in situations

where the hands are needed for supervision, manipulation, communication, or other parallel tasks.

Previous work has shown that teleoperation performance strongly depends on the design of the operator interface and the workplace design [6]. Human factors such as workload, situation awareness, cognitive demand, and control effort directly influence the effectiveness of teleoperated robot operation [7]. For road-vehicle teleoperation, recent studies have compared different interface and workplace design concepts [8], [9].

In parallel, substantial research has addressed the effects of communication delay and limited feedback in teleoperation. Workload-oriented delay compensation, predictor-based control, predictive video augmentation, and driver-assistance functions have been proposed to improve controllability under adverse communication conditions [10]–[12]. Nevertheless, the input side of the teleoperation loop has received comparatively less attention: most systems still rely on manual command devices. This motivates the investigation of alternative, wearable input modalities that can provide continuous vehicle commands while leaving the operator’s hands free.

B. Human–Machine Shared Control

Efficient teleoperation systems require advanced human–machine shared control, which aims to combine the adaptability of a human operator with the reliability and precision of automation. In such systems, both agents influence the same controlled plant, and the available control authority is distributed between them [13], [14]. This enables gradual assistance and smoother authority transitions, which are important for teleoperated vehicles operating under uncertainty.

The design of shared-control systems is difficult because the human operator and the automation may not always pursue identical actions. Conflicts can arise when the automation modifies or rejects an operator command, even if the command reflects the operator’s intention. Therefore, the literature identifies authority allocation, conflict management, and transparency as central design challenges [15]. Since human operators differ in behavior and control style, motivating approaches that explicitly account for human variability [16].

To address these issues, shared control is increasingly studied through optimal-control and adaptive authority-allocation methods. Representative examples include model-predictive haptic shared steering [17] and potential-field-based teleoperation [18]. Recent approaches also adapt control authority according to estimated trust or operator intention [19], [20]. Nevertheless, these methods mainly rely on conventional hand-based input devices, while wearable foot-based interfaces are rarely considered.

C. Foot-Based and Pedal Control Interfaces

Foot-operated input has been studied since early human–machine interaction research [21], and surveys describe a wide design space of foot- and pedal-based interfaces, sensing principles, and feedback modalities [3], [22]. A key motivation is hands-free operation, where the feet provide an additional input channel for mobile interaction [23] as well as locomotion and navigation in virtual environments [24].

In robotics, foot interfaces have mainly been explored for manipulation and surgery, where the operator’s hands are occupied. Continuous pedal-like interfaces can control robot arms more smoothly and intuitively than discrete buttons [25], and subject-specific four-degree-of-freedom foot interfaces have been developed for surgical robots [26]. Foot control has also been used as a “third hand” in three-handed teleoperation and multi-limb endoscopic surgery [27], [28], and recent work investigates hands-free teleoperation of nearby manipulators through body-to-robot links [5]. These studies demonstrate that feet can generate continuous multi-dimensional commands, but their focus is robotic manipulation rather than ground-vehicle teleoperation.

D. Research Gap

The literature reveals a clear gap: although foot interfaces enable continuous multi-degree-of-freedom control, teleoperation and shared control still mainly rely on hand-operated devices, despite growing evidence that the human operator is a key bottleneck [29]. Thus, wearable foot-based teleoperation of UGVs remains largely unexplored.

III. THE PROPOSED TELEOPERATION INTERFACE

A. Wearable foot interface

The proposed teleoperation interface is based on a custom Bluetooth Low Energy (BLE) wearable device. The device, further referred to as foot interface, is based on a motion sensor for measuring the 2D orientation of the operator’s foot. The foot interface is connected to the host computer, where its data are decoded and published.

B. Experimental Vehicle Platform

Validation measurements were performed using a RoboRacer-compatible compact unmanned ground vehicle platform designed for indoor robotics and teleoperation research. The vehicle is based on a small-scale Ackermann steering chassis equipped with electric four-wheel drive propulsion and a steering actuator. The platform incorporates onboard computation hardware (Nvidia Jetson Orin Nano) running a ROS 2-based software framework.

The RoboRacer platform [30] was selected due to its dynamic characteristics, which resemble those of full-scale ground vehicles while reducing operational risks and infrastructure requirements. The compact system enables indoor experimentation without dependence on environmental conditions and allows repeatable comparative measurements between different teleoperation methods using identical track configurations.

C. System Architecture

The proposed method converts the operator’s foot motion into vehicle commands through a ROS 2-based teleoperation pipeline. A BLE inertial sensor mounted on the operator’s foot provides orientation data. The host computer receives BLE notifications, decodes the orientation packet, applies offset calibration, filters the input signal, and publishes Ackermann drive commands to the vehicle control stack.

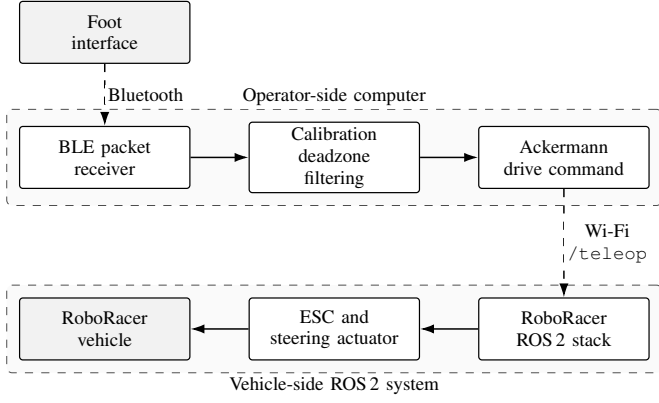


Fig. 1: System architecture of the proposed foot-based teleoperation interface. Dashed arrows indicate wireless communication links.

The foot controller provided joystick-equivalent commands through the same vehicle software interface, enabling a direct comparison with conventional joystick control.

The overall architecture is shown in Fig. 1. The foot-mounted BLE sensor sends data to an operator-side computer, where a Python-based ROS 2 node performs parsing, calibration, filtering, and command generation. The resulting commands are transmitted to the RoboRacer control stack.

D. Foot-Based Command Generation

The foot controller uses the roll and pitch orientation components of the BLE inertial sensor. At startup, the current sensor orientation is stored as the neutral foot pose. Subsequent measurements are expressed relative to this neutral pose.

$$\Delta\phi_k = \phi_k - \phi_0, \quad \Delta\theta_k = \theta_k - \theta_0, \quad (1)$$

where ϕ_k and θ_k are the measured roll and pitch angles at sample k , while ϕ_0 and θ_0 denote the neutral foot orientation recorded during calibration.

$$u_{\delta,k} = K_\delta \Delta\phi_k, \quad u_{v,k} = K_v \Delta\theta_k, \quad (2)$$

where $u_{\delta,k}$ and $u_{v,k}$ are the raw steering and longitudinal command signals, and K_δ and K_v are the corresponding scaling gains.

$$\text{dz}(u) = \begin{cases} 0, & |u| < u_{\text{dz}}, \\ u, & |u| \geq u_{\text{dz}}. \end{cases} \quad (3)$$

$$\begin{aligned} \delta_k &= \text{sat}_{[-\delta_{\text{max}}, \delta_{\text{max}}]}(\text{dz}(u_{\delta,k})), \\ v_k &= \text{sat}_{[-v_{\text{max}}, v_{\text{max}}]}(\text{dz}(u_{v,k})). \end{aligned} \quad (4)$$

$$\begin{aligned} \delta_{f,k} &= \alpha \delta_{f,k-1} + (1 - \alpha) \delta_k, \\ v_{f,k} &= \alpha v_{f,k-1} + (1 - \alpha) v_k, \end{aligned} \quad (5)$$

where $\alpha \in [0, 1]$ is the low-pass filter coefficient. The filtered values $v_{f,k}$ and $\delta_{f,k}$ are the speed and steering components of the Ackermann command. Because the commands are calculated relative to the neutral foot orientation recorded

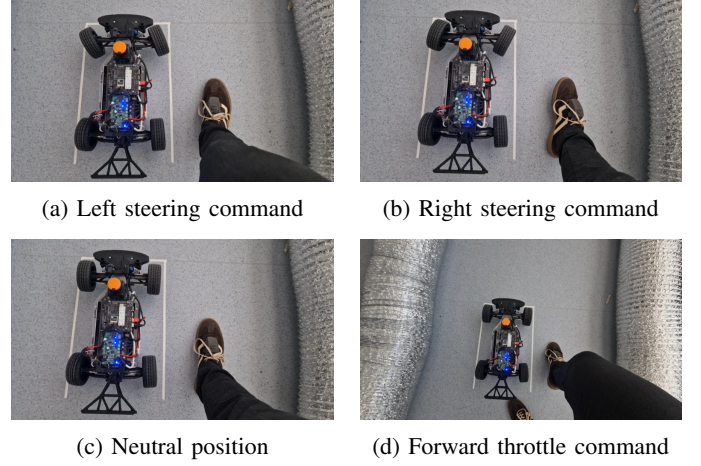


Fig. 2: Foot interface control commands used for vehicle operation.

TABLE I: Parameters of the foot-based teleoperation interface.

Parameter	Symbol	Value
Sensor model	—	WitMotion WT9011DCL
System update rate	f_s	20 Hz
Full-scale steering tilt	$\phi_{\delta,\text{max}}$	8°
Full-scale speed tilt	$\theta_{v,\text{max}}$	10°
Steering mapping gain	K_δ	0.125 deg^{-1}
Speed mapping gain	K_v	0.100 deg^{-1}
Normalized deadzone	u_{dz}	0.04
Maximum steering angle	δ_{max}	0.5 rad
Maximum forward speed	v_{max}	1.0 m/s
Previous-sample filter weight	α	0.15
Watchdog timeout	Δt_{max}	0.5 s

during calibration, the controller is insensitive to the initial sensor mounting angle and allows the operator to begin from a comfortable foot position. The first-order low-pass filter reduces rapid fluctuations and smooths the generated speed and steering commands.

The implementation parameters used during the experiments are summarized in Table I.

IV. EXPERIMENTAL FEASIBILITY STUDY

A. Experimental Setup

During evaluation, the vehicle was driven on a closed indoor track (see Fig. 3) containing straight sections and curved parts. The same environment and vehicle configuration were used for both investigated teleoperation methods.

Two input methods were compared. The first method was a conventional manual joystick serving as the reference interface. The second method was the proposed foot-based controller, where the operator controlled the vehicle through foot orientation measured by a BLE inertial sensor. Both methods were connected to the same ROS 2 vehicle stack and controlled the same Ackermann vehicle interface.

The experiments were carried out with four operators. Before the recorded trials, each operator received approximately 10 min of familiarization with the foot interface and test track;

Algorithm 1 Foot-based teleoperation algorithm.

Require: Foot-mounted IMU orientation stream (ϕ, θ)

Require: Calibration interval T_c , timeout $\Delta t_{\max}$

Require: Limits $v_{\max}$, $\delta_{\max}$ and filter coefficient α

Ensure: Ackermann drive commands published on `/teleop`

1: Initialize BLE interface and acquire valid IMU samples

2: Estimate neutral foot pose (ϕ_0, θ_0) over T_c

3: Initialize filtered commands: $v_f \leftarrow 0$, $\delta_f \leftarrow 0$

4: **while** teleoperation is enabled **do**

5: **if** a valid IMU sample is received within $\Delta t_{\max}$ **then**

6: Compute relative foot orientation:

$$\Delta\phi \leftarrow \phi - \phi_0, \quad \Delta\theta \leftarrow \theta - \theta_0$$

7: Map relative foot orientation to raw commands:

$$u_v \leftarrow K_v \Delta\theta, \quad u_\delta \leftarrow K_\delta \Delta\phi$$

8: Apply deadzone and saturation:

$$v \leftarrow \text{sat}_{[-v_{\max}, v_{\max}]}(\text{dz}(u_v)), \quad \delta \leftarrow \text{sat}_{[-\delta_{\max}, \delta_{\max}]}(\text{dz}(u_\delta))$$

9: Apply first-order low-pass filtering:

$$v_f \leftarrow \alpha v_f + (1 - \alpha)v, \quad \delta_f \leftarrow \alpha \delta_f + (1 - \alpha)\delta$$

10: Publish Ackermann command (v_f, δ_f) on `/teleop`

11: **else**

12: Publish zero-velocity safety command

13: **end if**

14: **end while**

these runs were not recorded or analyzed. Each operator then completed five recorded laps using the joystick followed by five laps using the foot-based controller. The condition order was fixed and was not counterbalanced.

During the experiments, video data from an overhead camera [31] was recorded and used for image-based path evaluation. The video recordings enabled the extraction of the vehicle path compared to track limits in image coordinates, which were then used to compare the mean lap paths obtained with manual and foot-based control.

B. Experimental Measures

The experimental comparison was evaluated from the detected vehicle-marker trajectory. For each participant and interface, the recorded path was segmented at the physical start/finish gate. An initial incomplete warm-up traversal, when present, was excluded before complete laps were enumerated. The first five consecutive complete laps were retained; any complete laps after the fifth were excluded by this count-based rule. This deterministic procedure was independent of the subsequently reported outcomes and yielded 40 analyzed laps.

Each retained lap was resampled to 300 equally spaced arc-length samples. A mean lap trajectory and pointwise path-spread values were then computed separately for each participant and interface. Trajectory smoothness was evaluated using the mean absolute change in unwrapped heading between consecutive trajectory segments. Let θ_i be the unwrapped heading angle of segment i , computed from consecutive trajectory points. The smoothness metric for a lap is defined as

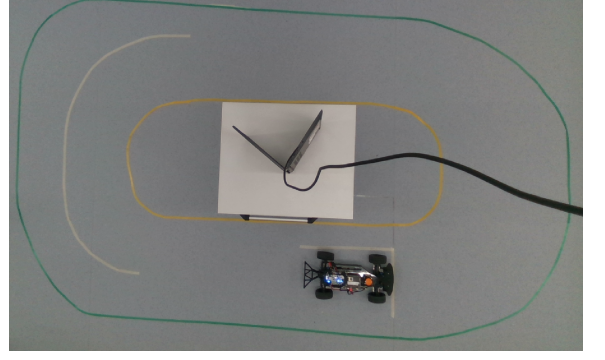


Fig. 3: Indoor test track used for comparing the proposed foot interface with manual joystick control.

$$S = \frac{1}{N-2} \sum_{i=1}^{N-2} |\theta_{i+1} - \theta_i|, \quad (6)$$

where N is the number of trajectory samples. Lower values indicate smoother trajectories with fewer abrupt steering corrections.

To quantify lap-to-lap repeatability, the deviation of retained lap i from the corresponding participant- and interface-specific mean trajectory was calculated using the root-mean-square (RMS) error

$$RMS_i = \sqrt{\frac{1}{M} \sum_{k=1}^M \|\mathbf{p}_{i,k} - \bar{\mathbf{p}}_k\|^2}, \quad (7)$$

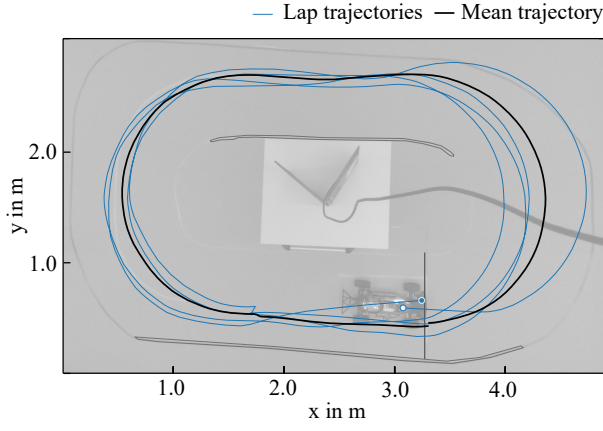
where $\mathbf{p}_{i,k}$ is the k th point of retained lap i , $\bar{\mathbf{p}}_k$ is the corresponding point of the participant- and interface-specific mean lap trajectory, and $M = 300$ is the number of re-sampled points. The participant-level RMS deviation reported in Table II is the mean of RMS_i over the five retained laps. The maximum deviation was calculated analogously as the largest pointwise Euclidean distance from the corresponding mean trajectory among those laps. Lower values indicate greater within-participant, within-interface trajectory repeatability; they do not measure deviation from an externally defined ideal path.

These quantities provide descriptive measures of controllability and within-condition repeatability in this feasibility pilot.

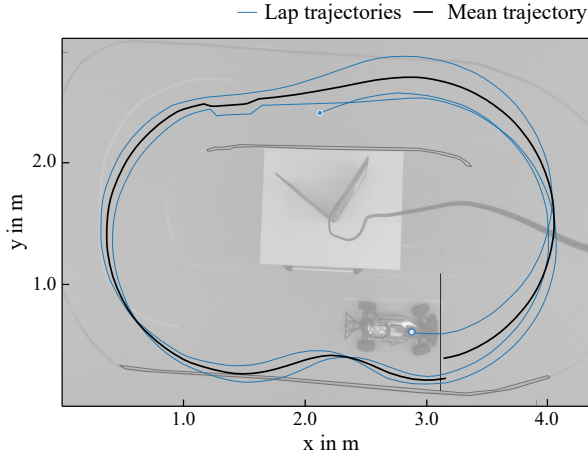
V. RESULTS AND DISCUSSIONS

A. Results of the Experiment

Table II presents the participant-level descriptive results. In the analyzed sample, joystick control generally produced shorter lap times, smoother trajectories, and lower trajectory-deviation values. However, this pattern was not uniform across every participant and metric: P2 completed the foot-control condition slightly faster, while P1 had a lower smoothness value with foot control. All four participants had lower RMS and maximum deviations with joystick control. Because the



(a) Hand controller input



(b) Foot interface input

Fig. 4: Representative single-operator trajectory examples for the two input modalities (Participant 1).

TABLE II: Participant-level descriptive trajectory metrics for foot and hand control.

ID	Control	Lap in s	Smooth. in rad	RMS dev. in m	Max dev. in m
P1	Foot	20.31	0.120	0.462	0.914
P1	Hand	9.34	0.162	0.115	0.160
P2	Foot	7.28	0.089	0.276	0.677
P2	Hand	7.85	0.042	0.158	0.462
P3	Foot	19.51	0.498	0.539	0.927
P3	Hand	11.54	0.045	0.232	0.492
P4	Foot	46.21	0.498	0.523	1.089
P4	Hand	11.65	0.045	0.215	0.408

study included only four operators and no inferential statistical analysis was performed, these observations describe the recorded sample only and do not establish population-level superiority or equivalence between the interfaces. The RMS and maximum-deviation measures quantify lap-to-lap repeatability relative to the corresponding mean trajectory; they do not measure accuracy relative to an ideal reference path.

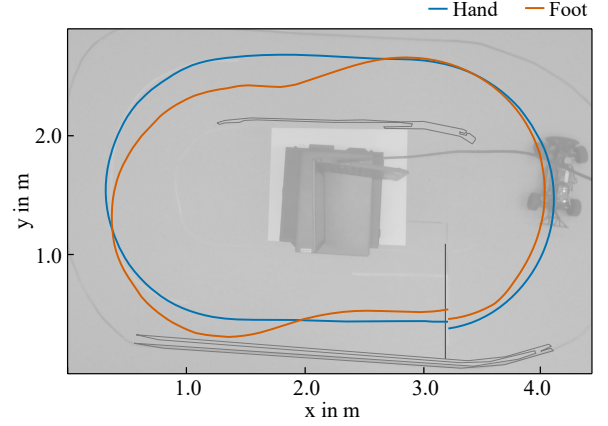


Fig. 5: Common mean lap paths computed from the laps of the foot-control and hand-control measurements.

B. Discussion and Limitations

In the analyzed sample, the descriptive results generally favored manual hand control. This pattern may partly reflect the operators' greater familiarity with joystick-based driving. However, the foot-control results demonstrate the feasibility of the proposed concept. The interface allowed the operators to guide the vehicle around the track without using their hands, and several complete laps were obtained. These results indicate that the proposed foot interface is a feasible hands-free teleoperation modality, particularly for scenarios in which conventional hand-operated control is unavailable, inconvenient, or would interfere with simultaneous operator tasks.

The main limitation of the current foot-control implementation is its lower repeatability. Compared with hand control, the foot-control trajectories showed larger inter-lap variation and lower smoothness. This can be attributed to the less familiar control modality. Operator experience may have influenced the observed performance, since participants were generally more familiar with conventional joystick-based control than with the proposed foot interface. The limited participant pool is sufficient for demonstrating technical feasibility, but a larger and more diverse user study would be required to assess inter-operator variability, learning effects, and the generalizability of the usability and performance results. These observations indicate clear directions for improvement, including adaptive neutral-pose calibration, participant-specific gain tuning, stronger filtering of unintended foot motion, and a short training phase before evaluation. Among these improvements, participant-specific calibration and gain tuning are expected to have the greatest immediate impact on usability, because the comfortable foot-motion range and preferred neutral position may differ substantially between operators. Adaptive filtering is also important for suppressing unintended movements, but it should be tuned carefully to avoid introducing excessive command delay.

The experiment should be interpreted as a feasibility pilot. The small sample size ($N = 4$) does not support general conclusions about comparative interface performance. In addi-

tion, all operators used the joystick first and the foot interface second. Greater familiarity with joystick control may have favored the hand-control condition, whereas experience gained on the track may have favored the subsequently performed foot-control condition. Although the operators received a 10-min familiarization period, this does not eliminate the fixed-order confound. Consequently, the observed differences are interpreted descriptively rather than as evidence of a causal interface effect.

VI. SUMMARY AND OUTLOOK

This paper presented and evaluated a foot-based teleoperation interface for a small-scale unmanned ground vehicle. All four operators successfully completed the track using the proposed interface, demonstrating its technical feasibility in the tested setting. The descriptive results generally favored joystick control, but the small sample and fixed condition order prevent population-level conclusions about the relative performance of the two interfaces. Future work will include a larger participant sample, counterbalanced condition order, and a standardized familiarization and training procedure.

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