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A comparative analysis of feedback delivery modality within a Precision Teaching protocol to enhance drivers' lane maintenance

Mariaelena Tagliabue [a,b,c], Giulia De Cet [b,c], Federico Orsini [b,a,c,*], Massimiliano Gastaldi [b,a,c], Riccardo Rossi [b,c]

[a] University of Padova, Department of General Psychology, Via Venezia 8, 35131 Padova, Italy
[b] University of Padova, Department of Civil, Environmental and Architectural Engineering, Via F. Marzolo 9, 35131 Padova, Italy
[c] Mobility and Behaviour Research Center – MoBe, University of Padua, 35131 Padua, Italy

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ABSTRACT

Precision Teaching (PT) is a data-driven educational technique that continuously monitors and adjusts instruction to achieve specific, measurable learning outcomes. This research applies PT principles to train drivers in improving lane maintenance behaviour, focusing on the comparison between feedback delivery modalities, to fill a gap in prior literature due to limited and somewhat conflicting findings.

This study builds upon a previous study, expanding the analysis to encompass a larger cohort of drivers and introducing a new experimental condition. Overall, 80 participants were involved in a driving simulator study in which they were asked to perform four consecutive trials, the first without feedback and others with feedback delivery.

Participants were divided into three groups, each assigned to an experimental condition based on feedback administration: Auditory (A), Visual (V), and combined (VA). All systems provided contingent negative/positive feedback based on participants' lateral position.

A MANOVA was conducted, with feedback type and trials serving as independent variables. The analysis considered six dependent variables, incorporating four indicators for lane maintenance, along with two variables, mean speed and acceleration, to assess potential indirect effects.

Results reveal that all tested conditions were effective. However, conditions A and VA demonstrated greater effectiveness in reducing the standard deviation of lateral position. The auditory feedback system seems to emerge as the most promising option, likely being less intrusive since it delivered fewer stimuli compared to VA. These findings could be valuable in shaping the design of PT protocols for real-time coaching programs for eco-driving or within usage-based insurance schemes.

1. Introduction

1.1. The concept of Precision Teaching

Precision Teaching (PT), first developed by Lindsley (1991), has been adopted by many behavioural analysts over the past few decades, leading to various definitions and descriptions. A recent work by Evans et al. (2021) evaluated 10 different common definitions of PT and synthesized it as "a system for precisely defining and continuously measuring dimensional features of behaviour […] to make timely and effective data-based decisions to accelerate behavioural repertoires" (Evans et al., 2021; p. 561). According to the same authors, the PT system can be subdivided into a sequence of five steps:

1. Pinpoint. A clear, measurable dependent variable is specified through the pinpointing process. This involves selecting a specific behaviour or set of behaviours to target and measure, along with setting an aim or final goal for the skill being taught.
2. Arrange Instruction or Practice. Precision teachers design effective instructional and practice materials and procedures to promote high accuracy and fluency.
3. Decide. Data are analysed, and a decision is made in the progress: keep going if steady growth is observed, make a change if progress

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* Corresponding author at: University of Padova, Department of Civil, Environmental and Architectural Engineering, Via F. Marzolo 9, 35131 Padova, Italy.
E-mail address: federico.orsini@dicea.unipd.it (F. Orsini).

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has stalled or deteriorated, or stop the current program if the learner has met the specified aim.

4. Try Again. Persistently observe, analyse, and make data-based decisions until success is achieved.

Within the second step, providing timely and effective feedback to the learner is a critical component of the instructional process; feedback should be specific, objective, and delivered immediately after the learner's response (Ericsson et al., 1993; Gallagher et al., 2006; Lindsley, 1991). Positive feedback for correct responses reinforces successful behaviours, while corrective feedback for errors helps learners identify and rectify mistakes. PT is well-suited for highly-structured tasks, in which there is a clear connection between the stimulus and the response (Merbitz et al., 2004). The complexity of the stimulus and the response is not a limitation for this technique: it can involve intricate configurations of signals, like lights or sounds, and complex actions, such as operating levers or buttons. However, for optimal effectiveness, a direct relationship between stimulus configurations and the elicited response is essential. This approach aims to establish automated behaviours minimizing the involvement of voluntary, conscious control (Binder, 1996).

1.2. Precision Teaching and driving

PT was first developed and applied in educational studies, e.g., to improve academic skills (McTiernan et al., 2022), learn languages (Beverley et al., 2016) or teach students with disorders/disabilities (Brady and Kubina, 2010). It has been then applied for other purposes, such as for sport performance improvement (Lokke et al., 2008; Pocock et al., 2010) or brain damage rehabilitation (Chapman et al., 2005; Kubina et al., 2000).

The concept of PT was formally introduced in the field of transportation by Biondi et al. (2020), in which a system to improve lane maintenance[1] was tested in three driving simulator experiments, the first involving a control group with no treatment, where participants were instructed to drive as they would normally do in the real world, the second in which participants were administered contingent auditory feedback based on their performance, and the third in which a redundant auditory-visual feedback was presented. In each experiment participants had to drive multiple times on the same route, in order to evaluate the learning progress. The second and third experiments included a baseline trial in which participants were instructed to drive naturally, consistent with the control group. Findings showed that the PT system was effective in improving lane maintenance, while redundant feedback did not provide additional benefits compared to the auditory-only. The inclusion of a control group which repeated the route four trials, always without any feedback, demonstrated absence of any learning/familiarisation effect on the dependent variables. Further driving simulator studies on the same system showed that such benefits were retained by participants when driving without any feedback one month later (Rossi et al., 2022a), and tested alternative visual feedback systems (Rossi et al., 2022b).

In the transportation literature there are other examples of teaching/coaching programs which implicitly adopted procedures that, to some extent, fall within the definition of PT. In a driving simulator study conducted by Hibberd et al. (2015), precision teaching principles were applied to eco-driving. Drivers received information about fuel consumption, either haptically through the accelerator pedal or through a combination of visual and auditory signals. The visual display indicated changes in accelerator pedal angle and fuel consumption with colour variations, while the concurrent pitch tone informed drivers about adjustments needed in pedal pressure to maintain low fuel consumption. Results showed that both haptic and visual-auditory signals led to more eco-friendly behaviours compared to the control condition without signals. Similar findings were reported in the naturalistic study by Barbé et al., (2007), where the combination of visual and auditory signals resulted in greater fuel consumption reductions compared to traditional classroom training. In the study by De Groot et al. (2011), participants drove a simulated vehicle in four conditions: receiving haptic signals when the vehicle was in the centre of the lane (on-target), haptic signals when the vehicle was away from the centre (off-target), with no haptic signal (control), and with realistic vibrations depending on engine speed. The results indicated that both on-target and off-target haptic signals led to improvements in lane maintenance compared to the control and realistic vibrations conditions.

1.3. Feedback delivery – Which modality is more effective?

The selection of the feedback delivery modality is crucial due to its potential impact on the effectiveness of PT.

Previous research has investigated the effectiveness of various signal modalities within in-vehicle warning systems; yet, a definitive consensus regarding the superiority of one modality over others has not been established. Nevertheless, studies have often demonstrated that combining different redundant signal modalities enhances effectiveness in comparison to unimodal systems (Fricke and Thüring, 2009). This observation was also corroborated in a recent literature review by Horberry et al. (2022).

Within the framework of PT or other coaching/training programs, the signals conveyed to drivers are not solely aimed at delivering information. Instead, they offer feedback to guide them toward adopting new behaviours or nudging them in that direction. In this context, research exploring the effectiveness of different modalities remains relatively scarce. A recent *meta*-analysis conducted by Sanguinetti et al. (2020) investigated the impact of various feedback designs on eco-driving. This study explored several hypotheses, including whether (i) haptic feedback is more effective than visual, (ii) auditory feedback was more effective than visual, (iii) multiple-modality is more effective than single-modality. However, due to the limited sample, only the third hypothesis could be tested, in particular showing that the combination of auditory and visual feedback is more effective than visual feedback alone.

McIlroy et al. (2017) investigated diverse alternative feedback systems for eco-driving in a driving simulator, encompassing visual, haptic, auditory modalities, as well as their combinations. While their findings tentatively suggested that unimodal visual feedback might be less effective, the lack of statistical significance prevented a firm conclusion. Similarly the driving simulator study by Azzi et al., (2011), did not observe any statistical difference in the effectiveness of visual and haptic feedback modalities within their eco-driving assistance system.

In the context of usage-based insurance schemes there is a lack of literature directly comparing feedback delivery modalities. A driving simulator study by Dijksterhuis et al. (2016) did compare several different visual interfaces, with varying levels of detail in the information presented to drivers via in-vehicle-devices. The system evaluated drivers' performance based on their speeding behaviour and the harshness in lateral and longitudinal control, considering g-forces while accelerating, braking, and cornering. Interestingly, no significant differences were observed between visual interfaces providing real-time information on all variables, including monetary incentives, and simpler interfaces that conveyed information solely on speed or g-forces. This could be interpreted as an indication that the attention given to visual feedback is limited, as it also overlaps with the other visual stimuli related to the act of driving, possibly suggesting that alternative delivery modalities could be more effective.

The study by Hibberd et al. (2015) mentioned in Section 1.2 partly supports this hypothesis, by showing that an haptic feedback was more effective that a combined visual-auditory feedback in communicating

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[1] Consistent with Biondi et al. (2020), here and throughout this paper we refer to "lane maintenance" as the ability of drivers to maintain a correct lateral position within the lane, while exercising precise lateral control of the vehicle.

over-acceleration in their eco-driving program. The authors also noted that participants exposed to visual-auditory feedback spent less time looking at the road. However, crucially, the authors did not have the opportunity to directly compare the effects of different unimodal deliveries.

1.4. Study motivation, objective, novelty, and relevance

This study is motivated by lack of literature evidence addressing the effectiveness of different feedback modalities in training/coaching driving programs, particularly within the context of PT applications to driving. The study's aim is to assess and compare auditory, visual, and multimodal auditory-visual feedback systems within a PT program focused on enhancing lane maintenance skills.

The choice to focus on training lane maintenance was motivated by safety concern. Inadequate lateral position within the lane and/or poor lateral control, often as a result of some kind of impairment (e.g., drowsiness, distraction, alcohol usage), may result in road departures and head-on collisions, which in 2022 accounted for 26.5 % and 12.6 % of road fatalities in the USA, respectively (National Safety Council, 2024). Providing drivers with a strong base ability to maintain a steady, correct lateral position within the lane can arguably mitigate the risk of such crashes, as maintaining a correct and steady lateral control of the vehicle is a fundamental ability that people should master to drive safely (De Groot et al., 2011).

This investigation builds upon the preceding work conducted by Biondi et al. (2020), which incorporated auditory and auditory-visual feedback systems, and yielded some findings that were contrary to research expectations. In particular, it was expected that the multimodal delivery would have enhanced the effectiveness of the system, but both the multimodal and the auditory-only feedback systems resulted in similar improvements on the lane maintenance variables investigated (i.e., mean lateral position, standard deviation of lateral position, and standard deviation of steering angle). Hence, the present study places a specific focus on the feedback modality, to provide more insight into how it modulates the effectiveness of a PT protocol.

The primary research objective is to compare the effectiveness of visual, auditory, and multimodal visual-auditory feedback delivery modalities to identify the most suitable one within a PT protocol applied to driving training. Differently to our previous research, this study also includes analysis of some variables (speeding and acceleration) not strictly related to lane maintenance, aiming to uncover possible indirect effects on other driving variables. The rationale here was to investigate whether participants while being trained to maintain steady lateral control of the vehicle would also improve the smoothness of their longitudinal control; this stemmed from previous research indicating a complementary relationship, i.e., that a real-time feedback system aimed at nudging drivers toward smoother longitudinal control, was reported to indirectly enhance lateral control as well (Orsini et al., 2021). In addition, both speeding and acceleration/deceleration behaviour have meaningful safety implications; therefore, it is relevant to evaluate any indirect impact on them when assessing the PT protocol tested in the present study.

Significantly, to address potential limitations related to the limited size of the auditory-visual group in Biondi et al. (2020), additional participants were enlisted for this study; furthermore, a new group was introduced, receiving visual-only feedback. The procedure design was aligned to the recommended structure for a PT approach (as detailed in Section 2.7), which is a unique example within the field of transportation. This provides robust theoretical foundation to both the feedback system and experimental design.

The objective of this study holds practical relevance. The PT system tested here was designed as an offline (i.e., in a controlled laboratory environment) training tool intended for driver education or re-education. The outcomes have the potential to identify the most effective feedback modality for such systems. Additionally, these findings could be extended to systems designed for offline training of other driving skills (e.g., eco-driving enhancement or speeding reduction), or for on-road ITS-based coaching programs, such as those within usage-based insurance schemes.

Specifically, the research hypotheses tested in this study are:

1. The visual feedback system is less effective than the auditory and bimodal systems. Since Biondi et al. (2020) demonstrated a similar effectiveness of auditory and bimodal feedback systems, we expect to confirm these results here, even with an increased sample size and additional dependent variables. This would indicate a predominant contribution of the auditory part of the feedback. Consequently, we also expect that the visual system alone would be less efficient.
2. A PT protocol aimed at improving lane maintenance could have significant indirect impacts on longitudinal control, with additional safety implications. Considering what was observed in Orsini et al. (2021), it was hypothesized that an improvement in lateral control would be accompanied by a reduction in average speed and acceleration.

2. Material and methods

The experiment employed a driving simulator and included three distinct experimental conditions. Each participant was assigned to a specific experimental condition, all of which investigated the influence of PT on driving lane maintenance and potential indirect effects on variables such as speed and acceleration.

2.1. Participants

The study involved a total of 80 volunteers (40 women, 40 men) aged 19–35 years (mean = 23.7 and standard deviation = 3.30). To be eligible for participation in the experiment, individuals had to meet several criteria: 1) possess a driver's license for at least one year, 2) have driven a minimum of 1,000 km in the past year, 3) no prior experience with a driving simulator, and 4) not be affected by colour blindness. Participants received no monetary compensation for participating in the study. The experimental protocol was approved by the Ethical Committee for the Psychological Research of the University of Padova (IRB N 3024 06/06/2019).

Two participants withdrew from the simulation due to simulator sickness, experiencing discomfort such as nausea or dizziness while using the driving simulator. Consequently, data analysis was conducted on the remaining 78 participants.

Participants were divided into three groups, each assigned to an experimental condition based on the type of feedback administered (see Table 1):

- 29 participants received auditory feedback (Condition A).
- 25 participants received visual feedback (Condition V).
- 24 participants received feedback in both auditory and visual modalities (Condition VA).

Table 1
Characteristics of participants in the three different feedback conditions. Ranges in squared brackets. Annual mileage refers to how much participants drove in the last year; driving experience to how long they have held a driver's license.

Feedback Type	Part. N	Gender	Age	Annual mileage [km]	Driving experience [years]
A	29	13F; 16 M	24.0 [19–35]	6,326 [1,000–30,000]	5.1 [1–12]
V	25	13F; 12 M	23.8 [19–29]	8,920 [1,000–25,000]	5.4 [1–11]
VA	24	12F; 12 M	22.9 [20–28]	8,975 [1,000–30,000]	4.4 [1–10]

Condition A comprised participants recruited for the study conducted by Biondi et al. (2020). Condition VA consisted of a combination of participants from the aforementioned study and new participants. Condition V constituted an entirely new experimental group.

Participants were informed about the specific skill being assessed during the trials, as a previous study evidenced that this has a positive impact in terms of effectiveness within the context of a PT protocol for driving training (Rossi et al., 2020a).

2.2. Apparatus

A fixed-base driving simulator (STSoftware®) located at the Transportation Laboratory of the Department of Civil, Environmental and Architectural Engineering (DICEA) of the University of Padova was used to conduct the experiments (Fig. 1). The simulator is equipped with an adjustable seat with seat belt, a steering wheel with dynamic force feedback with a steering angle of 900° turn angle and gas, brake and clutch pedals. Around the cockpit, five full high-definition screens with a resolution of 1,920x1,080 pixels were placed in order to create a field of view of 330° horizontally and 45° vertically. The simulator is also equipped with 3 networked computers. A Dolby Surround® 5.1 system produced simulated engine, road and traffic sounds to help immerse the driver during the driving experience. Kinematic data were collected with a sampling rate of 50 Hz.

2.3. Experimental design and procedure

Before taking part in the experiment, participants provided personal information and completed the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993) to assess factors related to the onset of simulator sickness. To mitigate the onset of drowsiness, fatigue and simulator sickness, the average temperature in the room was set between 20 °C and 22 °C, and the illuminance was set at 4 lx.

Following the initial instructions provided in a written form, participants underwent a training phase lasting approximately 10 min. The training phase involved driving in a distinct test environment which consisted of straight and curved segments, T intersections, and a roundabout, comprising both urban and rural settings. During this phase, participants had the opportunity to accelerate through all gears, decelerate to bring the vehicle to a stop, and execute steering manoeuvres in both directions.

After this training, they filled out the SSQ questionnaire. Subsequently, each participant conducted the first trial, referred to as the “baseline” trial (with no feedback), followed by three consecutive trials with feedback. Before the baseline run and before each of the three subsequent driving runs, participants received specific instructions based on their experimental conditions; in particular, for the baseline trial they were instructed to drive as they would normally do in the real world, whereas for the successive trials they were made aware of the presence of the feedback system and of its basic functioning. Depending on the experimental group, visual and/or auditory feedback was administered. Participants received clear information about which feedback was positive and which was negative, and they were told that this would depend on their lane maintenance ability. Technical details, such as the specific width of the correct area were not known to the participants. No specific incentive was tied to better lane performance.

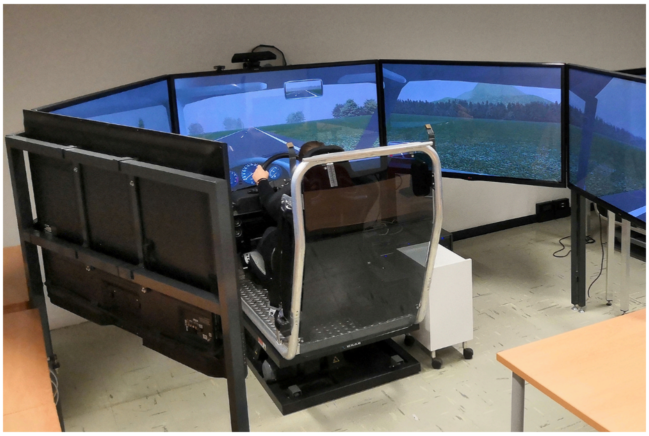

Fig. 1. The Transportation Laboratory at the Department of Civil, Environmental and Architectural Engineering of the University of Padova.

While the baseline (control) route was identical for all participants, the set of three successive trials varied for each of the three experimental conditions, A, V, and VA (see Fig. 2).

Upon completing the driving sessions, participants were asked to fill out the SSQ questionnaire once again. The entire experiment had a total duration of approximately 60 min.

2.4. Virtual scenario

The scenario was designed in virtual reality with the 3D editor software of the driving simulator and was characterized by a dual-lane roadway (each lane was 2.95 m wide) with two-way traffic and low traffic conditions in the opposite direction (flow rate of about 300 vehicles/hour/lane). The simulator has been validated in previous studies (Rossi et al., 2020b, Rossi et al., 2014). The road had a length of 10 km and was composed of a sequence of 28 alternating left and right turns, preceded by a 200 m straight. Each curve was, had a radius of 500 m, and was 350 m long.

The driving route was divided into three sections, based on the surrounding environment and corresponding speed limits: rural (70 km/h speed limit, 2 km length), urban (50 km/h, 2 km), and rural (90 km/h, 6 km).

Including curved sections resulted in a more challenging task, requiring drivers to continuously adjust their steering input. The rationale behind this decision was twofold. Firstly, due to the increased task difficulty, there was greater potential for improvement in lane maintenance performance, mitigating the risk of a floor effect that could mask the effectiveness of PT. Secondly, this design ensured a sustained significant cognitive load on participants, minimizing the likelihood of passive task-related fatigue (May and Baldwin, 2009), which is known to degrade vehicle lateral control (Thiffault and Bergeron, 2003). The choice of dividing the route into sections with different speed limits and

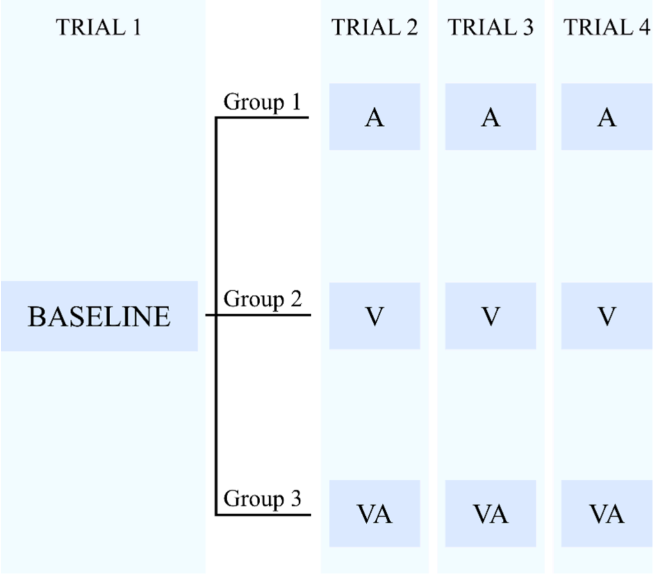

Fig. 2. Experimental design.

surroundings was also aimed at reducing the monotony of the driving task and mitigating the occurrence of passive task-related fatigue.

2.5. Feedback systems

As previously mentioned, participants were divided into three groups: each group was assigned to an experimental condition that differed in the type of feedback presented during the driving sessions. This feedback was intended to monitor the position of the vehicle with respect to the lane and informing drivers whether the position of their vehicle longitudinal axis was correct (positive feedback) or incorrect (negative feedback). The correct area was defined with a 50 cm width, positioned 25 cm to the right of the lane axis, in accordance to the Italian Highway Code (Art. 143–1), which requires vehicles "to drive on the right-hand side of the carriageway and near the right-hand edge of the carriageway, even when the road is clear" (Fig. 3).

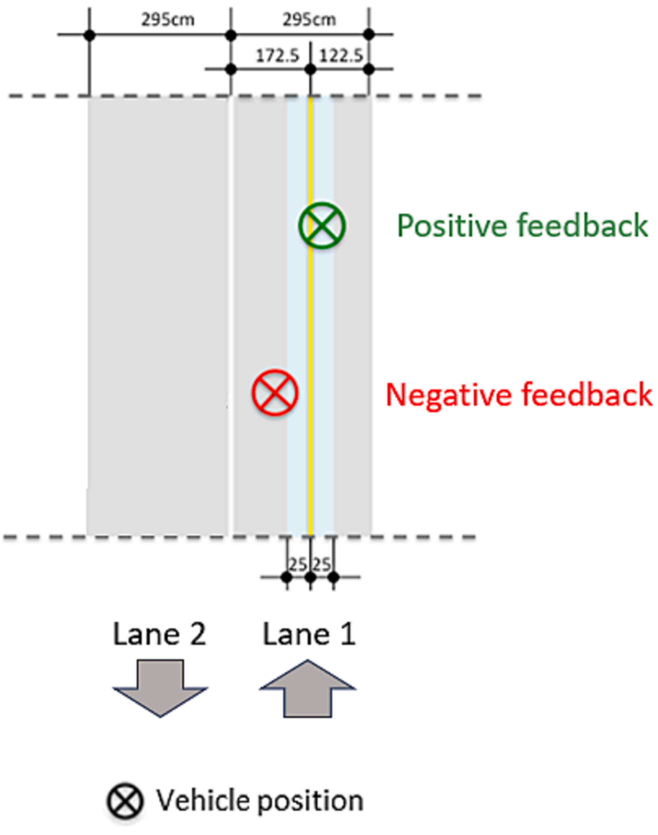

Fig. 3. Positive and negative feedback zones.
Adapted from Biondi et al. (2020).

By nudging drivers to keep within a relatively narrow correct area, the system was designed with the objective of improving lane maintenance. Consequently, it aimed to ensure that drivers maintain a proper position within the lane while improving their lateral control.

Each of the three groups had a different type of feedback, based on the assigned experimental condition:

- ***Auditory feedback (A):*** consisting of two signals, both lasting 0.92 s, a high-pitch one (400 Hz fundamental frequency) when the vehicle entered the positive feedback zone (Fig. 3), and a low-pitch one (125 Hz fundamental frequency) when the vehicle moved away into the negative feedback zone. The intensity with simulator ambient sounds and either auditory feedback active was about 78 dBA; the intensity with only simulator ambient sounds was about 60 dBA (these are not fixed values, as they depend on engine RPMs). Sound intensity was evaluated with the setup described in Orsini et al. (2024).
- ***Visual feedback (V):*** consisting of a 2D image of a circle positioned in the upper part of the screen, with its centre located 18 cm above the line of sight (within 10° of the driver's visual angle). The circle was green (Fig. 4) when the vehicle was within the correct area, and red otherwise.
- ***Visual-auditory feedback (VA):*** a multimodal feedback system including both the above-described auditory and visual cues, activated simultaneously.

2.6. Variables and analysis

All the analyses were carried out with IBM SPSS 22 statistical package. A multivariate analysis (MANOVA) was carried out on the standardized simulator performance scores, with two independent variables, i.e., *feedback type* (3 levels: V-visual, A-auditory, VA-visual/auditory) and *trial* (4 levels), and six dependent variables:

1. Mean absolute Lateral Position (ABSLP) in m,
2. Standard Deviation of Lateral Position (SDLP) in m,
3. Mean absolute lateral speed (LATSPEED) in m/s,
4. Standard Deviation of Steering Angle (SDSTEER) in degrees,
5. Mean speed (SPEED) in m/s,
6. Mean absolute acceleration (ACC) in m/s^2.

Factor *trial* can be considered as a marker for PT effectiveness, especially taking into account the results of the control group included in the study by Biondi et al. (2020), which excluded possible confounding learning/familiarisation effects.

Among the dependent variables, ABSLP, SDLP, LATSPEED, SDSTEER

Fig. 4. Visual feedback system. On the left, the positive feedback (green circle), on the right the negative feedback (red circle). Measures are expressed in meters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

were all directly associated with the feedback activation which, as described in Section 2.4, aims to enhance drivers' lane maintenance behaviour.

ABSLP was employed to monitor participants' ability to maintain as close as possible to the optimal lateral position. In the calculation of ABSLP, the reference "zero" for the lateral position was the axis of the correct area, which, as described in Section 2.5, was located 25 cm to the right of the lane axis. ABSLP is almost perfectly inversely correlated with the percentage of time spent within the correct area, Pearson's $r(310) = -0.985$, $p < 0.001$.

SDLP was used to assess how much drivers oscillate in terms of lateral position. A steady vehicle lateral control would yield low values of SDLP. However, low values of SDLP could potentially be achieved even with small, frequent, and quick corrections, which may still not be ideal in terms of lateral control. Hence, LATSPEED (i.e., the mean speed component perpendicular to the lane axis) was also included in the analysis, with small LATSPEED values serving as an additional indicator of better lane maintenance performance.

Steering movements are also reliable indicators of lane maintenance ability (Eriksson and Stanton, 2017; Hartman et al., 2016; Pawar and Velaga, 2021). SDSTEER measures the variance in steering angle, with steady lateral control being associated with smaller SDSTEER values.

SPEED and ACC were included in the analysis to investigate potential indirect effects on the longitudinal control of the vehicle.

Data collection started at the end of the initial 200 m straight and ended upon completion of the 10 km drive, therefore excluding both the initial acceleration phase and the final deceleration phase. The dependent variable values were computed by aggregating data from each complete driving task; they were subsequently standardized to align the baseline trial values for all feedback types and provide more robust comparative analysis of feedback delivery modality. The standardized values of each dependent variable were obtained with the following formula (Glantz et al., 2016; Pastore, 2015):

$$z = \frac{x - \bar{x}_{baseline}}{S_{baseline}} \quad (1)$$

Where z is the standardized score of value x ,$\bar{x}_{baseline}$ and $S_{baseline}$ are respectively the mean value and the standard deviation of the dependent variable, across all participants, in the baseline trial.

MANOVA was chosen for its capability to examine various dependent variables simultaneously, thus providing a comprehensive view of complex data relationships, while controlling the over-inflation of Type I error (Boyle et al., 2008; Rakauskas et al., 2004; Wu et al., 2018).

Effect sizes were estimated using η_p^2. As a rule of thumb, η_p^2 between 0.01 and 0.06 indicates a small effect, between 0.06 and 0.14 a medium effect, and greater than 0.14 a large effect (Cohen, 1988). Confidence intervals in Figs. 5 and 6 were computed as in Morey (2008).

Post-hoc pair comparisons were made with the Bonferroni correction for multiple comparisons.

2.7. Alignment with PT protocols

The procedure adopted in this driver simulator experiment follows the general structure of PT outlined in Section 1.1, with some exceptions discussed below. Specifically:

1. Pinpoint: Lane maintenance was identified as the target ability for training, and a set of dependent variables were identified to measure it. We did not set a specific final goal here, as the main aim of the experiment was to compare feedback modalities rather than achieving specific values of the dependent variables. This is further discussed at point 4 down below.
2. Arrange Instruction. Various feedback systems were developed (Section 2.5) to train participants. This aspect represents the core focus of the present experiment, which aimed to study and compare the effects of different feedback delivery modalities.
3. Chart. Each trial, involving driving in the 10 km scenario detailed in Section 2.4, served as the observation unit. Performance was assessed by analysing the trends in lane maintenance variables across trials.
4. Decide. In a PT protocol, the training ends for each subject upon reaching the target goal. However, in line with the study's objective to compare feedback systems, it was necessary to have an equal number of observations for each participant. This number was set at four, based on a pilot test using a different visual feedback that showed no additional improvements on SDLP after the fourth trial (Rossi et al., 2017).
5. Try Again. According to a PT protocol, learners who fail at reaching their goals continue training, possibly with adjustments to the protocol itself. This was not implemented in the current experiment, as beyond its scope.

A couple of additional aspects are worth noting.

Firstly, although this experiment deviates from points 1, 4, and 5 of a PT protocol, the tested systems could be applied in a stricter PT manner in real-world scenarios, with learners performing trials until they achieve their lane maintenance goal.

In addition, lane maintenance skills were always assessed with the feedback system active; the experiment did not investigate skill retention after feedback removal. Exploring this aspect would enhance the real-world relevance of the tested system, and it is proposed as a future research direction, as detailed in Section 4.4.

3. Results

This section illustrates the results obtained from the statistical analysis. Discussion and interpretation of the results are given in Section 4.

Table 2 illustrates the descriptive statistics for each of the six dependent variables, across the three feedback types and the four trials. As explained in Section 2.6, these values were then standardized before carrying out the MANOVA.

At a multivariate level, the *feedback type* factor reached significance with $F(12,140) = 5.98$, $p < .001$, $\eta_p^2 = 0.34$, Wilks' lambda $= 0.437$, as well as the *trial* factor with $F(18,58) = 27.43$, $p < .001$, $\eta_p^2 = 0.90$, Wilks' lambda $= 0.105$. The interaction between *feedback type and trial* was also significant, with $F(36,116) = 3.65$, $p < .001$, $\eta_p^2 = 0.53$, Wilks' lambda $= 0.220$.

3.1. Trial factor

Regarding the *trial* factor, at the univariate level, a significant effect was found on all the dependent variables (Table 3). Post-hoc pair comparisons are presented in Table 4. This indicates a relevant overall effect of the PT protocol.

In this section, we will outline the trends of the three variables (i.e., LATSPEED, SDSTEER, ACC) that showed significance in relation to the *trial* factor at the multivariate level, without showing any significant interaction with the *feedback type* factor. Subsequently, in Section 3.2, we will describe the trends of variables significant with respect to the interaction.

In Fig. 5a, standardized **LATSPEED** displayed a reduction in lateral speed following the introduction of feedback, but this effect was primarily noticeable in trial 2, with stability observed in trials 3 and 4.

Fig. 5b portrays the trend of standardized **SDSTEER**, which indicated an initial reduction in the standard deviation of steering wheel movements, signifying improved performance due to feedback presence. However, this advantage seemed to diminish in trial 4. Nevertheless, as detailed in Table 4, the performance in trial 4 was significantly better than that in trial 1.

Table 2
Mean and standard deviation for each dependent variable computed for each feedback type and trial.

Variable	Feedback type	Baseline		T2		T3		T4	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
ABSLP [m]	V	0.309	0.089	0.169	0.039	0.157	0.042	0.153	0.041
	A	0.286	0.097	0.228	0.107	0.186	0.076	0.152	0.052
	VA	0.257	0.093	0.162	0.065	0.134	0.024	0.130	0.032
SDLP [m]	V	0.238	0.062	0.191	0.046	0.178	0.044	0.176	0.045
	A	0.265	0.051	0.187	0.036	0.176	0.043	0.159	0.043
	VA	0.239	0.054	0.174	0.038	0.156	0.036	0.147	0.042
LATSPEED [m/s]	V	0.133	0.025	0.111	0.019	0.110	0.022	0.112	0.024
	A	0.146	0.041	0.111	0.030	0.106	0.030	0.103	0.027
	VA	0.133	0.042	0.104	0.026	0.100	0.027	0.099	0.029
SDSTEER [deg]	V	10.085	0.850	9.755	0.833	9.902	1.006	10.114	1.337
	A	8.811	2.816	7.848	1.121	7.820	1.140	7.754	0.941
	VA	8.650	1.294	8.131	1.242	8.077	1.385	8.177	1.579
SPEED [m/s]	V	20.659	1.671	20.160	1.682	20.666	1.940	21.063	2.535
	A	20.292	2.815	19.567	2.813	19.427	2.022	19.464	1.788
	VA	20.475	2.580	19.810	2.550	19.682	3.175	19.739	3.418
ACC [m/s^2]	V	0.134	0.059	0.126	0.068	0.114	0.058	0.118	0.071
	A	0.176	0.090	0.147	0.094	0.145	0.080	0.139	0.079
	VA	0.190	0.075	0.150	0.061	0.139	0.063	0.139	0.081

Table 3
Trial factor effects at univariate level.

Variable	df	df(Error)	*F*	*p*	η_p^2
ABSLP	3	225	125.98	<.001***	0.63
SDLP	3	225	210.76	<.001***	0.74
LATSPEED	3	225	84.13	<.001***	0.53
SDSTEER	3	225	10.42	<.001***	0.12
SPEED	3	225	4.22	=.016**	0.05
ACC	3	225	17.08	<.001***	0.19

Significance codes: *** p-value < 0.01; ** p-value < 0.05; * p-value < 0.1;
//: non-significant.

Table 4
Post-hoc comparisons across trials.

Variable	1–2	1–3	1–4	2–3	2–4	3–4
ABSLP	<.001***	<.001***	<.001***	<.001***	<.001***	=.001***
SDLP	<.001***	<.001***	<.001***	<.001***	<.001***	<.001***
LATSPEED	<.001***	<.001***	<.001***	//	//	//
SDSTEER	<.001***	<.001***	=.020**	//	=.056*	=.055*
SPEED	<.001***	=.021**	//	//	=.085*	//
ACC	<.001***	<.001***	<.001***	=.022**	=.092*	//

Significance codes: *** p-value < 0.01; ** p-value < 0.05; * p-value < 0.1; //: non-significant.

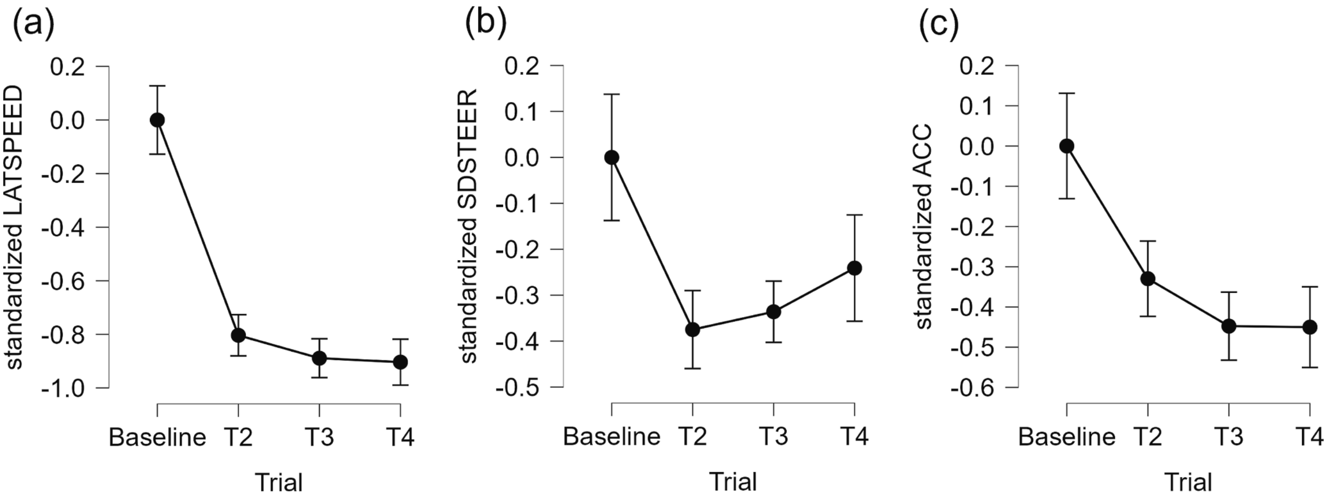

Fig. 5. Effects of Trial factor on dependent variables (a) LATSPEED, (b) SDSTEER, (c) ACC, reported with standardized values. Vertical bars represent 95% confidence intervals.

As illustrated in Fig. 5c, standardized **ACC** exhibited a reduction following the introduction of feedback during trials 2 and 3, remaining stable in trial 4.

3.2. *Feedback type factor and its interaction with trial factor*

In terms of the significance of the *feedback type* factor, at the univariate level we identified a significant effect on two dependent variables: SDLP, $F(2,75) = 5.33$, $p = .007, \eta_p^2 = 0.12$, and ABSLP, $F(2,75) = 5.04$, $p = .009$, $\eta_p^2 = 0.12$.

When considering different feedback types, the mean values for standardized **SDLP** revealed that in the V condition (−0.69), the standard deviation of lateral position was significantly greater compared to the other two conditions (A: mean = -1.33, $p = .002$; VA: mean = -1.12, $p = .039$). Conversely, for standardized **ABSLP**, the mean absolute lateral position in condition V (−1.25) was significantly lower than in the A condition (mean = -0.75, $p = .002$) and marginally lower than in condition VA (mean = -0.93, $p = .054$).

The interaction between *feedback type* and *trial* had a significant effect on three dependent variables: SDLP ($F(6,225) = 7.47, p < .001$ $\eta_p^2 = 0.17$), ABSLP ($F(6,225) = 4{,}36$, $p = .003$, $\eta_p^2 = 0.10$), and SPEED ($F(6,225) = 2.46$, $p = .046$, $\eta_p^2 = 0.06$). These interactions can be interpreted by observing Fig. 6. Post-hoc comparisons are reported in Tables 5 and 6.

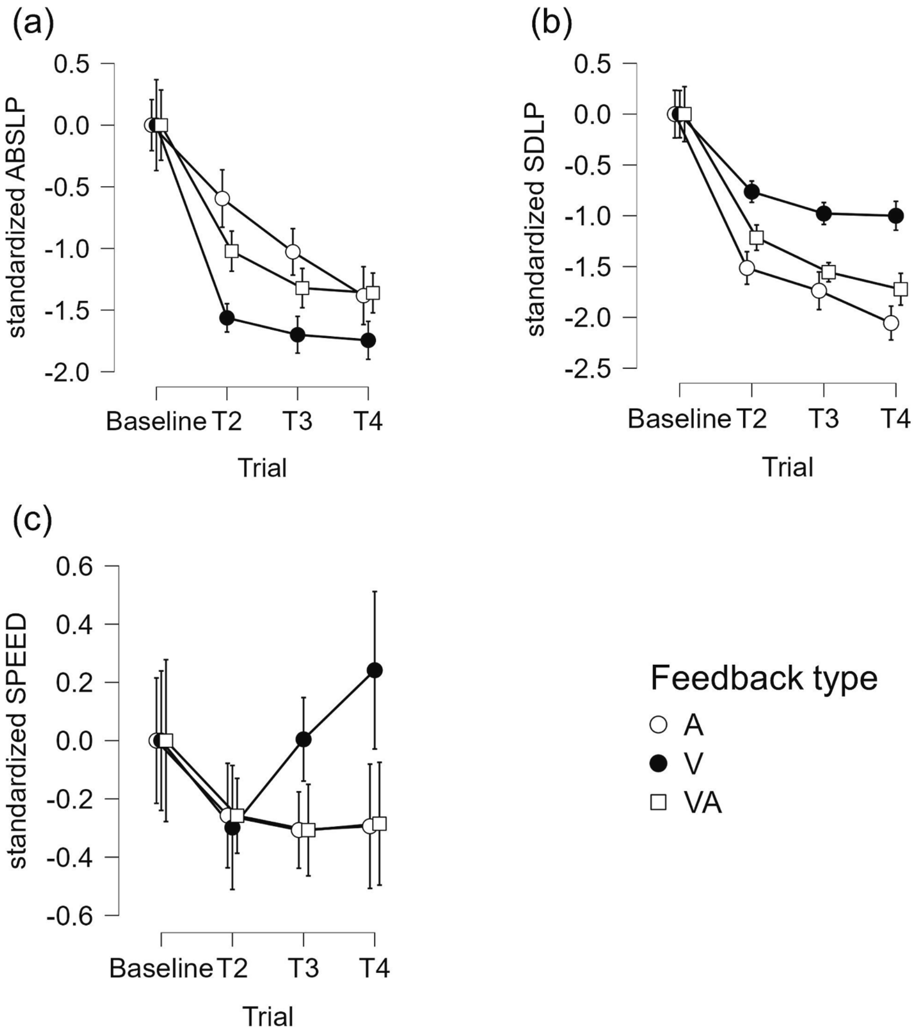

Fig. 6. Interaction effects of Feedback Type (A: Auditory, V: Visual, VA: Visual-Auditory) and Trial factors on dependent variables (a) ABSLP, (b) SDLP, (c) SPEED, reported with standardized values. Vertical bars represent 95% confidence intervals.

Table 5
Post-hoc comparisons across trials for each type of feedback group.

Variable	Feedback type	1–2	1–3	1–4	2–3	2–4	3–4
ABSLP	V	<.001***	<.001***	<.001***	//	//	//
	A	=.001***	<.001***	<.001***	=.001***	<.001***	<.001***
	VA	<.001***	<.001***	<.001***	=.096*	//	//
SDLP	V	<.001***	<.001***	<.001***	//	//	//
	A	<.001***	<.001***	<.001***	=.068*	<.001***	<.001***
	VA	<.001***	<.001***	<.001***	=.004***	<.001***	//
SPEED	V	//	//	//	=.045**	=.007***	//
	A	//	//	//	//	//	//
	VA	//	//	//	//	//	//

Significance codes: *** p-value < 0.01; ** p-value < 0.05; * p-value < 0.1; //: non-significant.

Table 6
Post-hoc comparisons across type of feedback groups for each trial.

Variable	Trial	V-A	V-VA	A-VA
ABSLP	TRIAL 1	//	//	//
	TRIAL 2	<.001***	=.069*	//
	TRIAL 3	<.001***	=.067*	//
	TRIAL 4	=.016**	=.014**	//
SDLP	TRIAL 1	//	//	//
	TRIAL 2	=.001***	=.091*	//
	TRIAL 3	=.001***	=.026**	//
	TRIAL 4	<.001***	=.006***	//
SPEED	TRIAL 1	//	//	//
	TRIAL 2	//	//	//
	TRIAL 3	//	//	//
	TRIAL 4	//	//	//

Significance codes: *** p-value < 0.01; ** p-value < 0.05; * p-value < 0.1 //: non-significant.

Regarding the standardized **ABSLP** variable (Fig. 6a), within the V group, trial 1 displayed a significant difference ($p < .001$) compared to all other trials, which, in contrast, exhibited similar outcomes among them. Notably, the introduction of feedback led to an initial improvement that then remained consistent in subsequent trials. In the A group, trials 1, 2, 3, and 4 demonstrated significant distinctions from one another ($p < .001$). Similarly, the introduction of feedback resulted in an initial improvement that persisted in subsequent trials. Lastly, the trend in the VA group resembled that of the V group, with significant differences only noted between trial 1 and the other trials ($p < .001$). Post-hoc tests revealed no significant difference between A and VA groups in any trial (Table 6).

Regarding standardized **SDLP** (Fig. 6b), in the V group, trial 1 exhibited a significant deviation from all the following trials ($p < .001$) which, among them, demonstrated comparable performance. Notably, the introduction of feedback resulted in an initial improvement that persisted over time. In the case of the A group, trial 1 showed a significant difference from all the other trials ($p < .001$), and trial 4 also differed significantly from the remaining trials ($p < .001$). In contrast, trials 2 and 3 exhibited similar outcomes. A significant improvement was observed in Trial 2, remained consistent in trial 3 and further increased in trial 4. For the VA group, trials 1 and 2 displayed notable distinctions from all other trials, while trials 3 and 4 exhibited similar performance. Again, no significant difference between A and VA groups was reported in any trial.

As regards the standardized **SPEED** variable (Fig. 6d), in the V group, a noteworthy deterioration was observed between trial 2 and 3, as well as between trial 2 and 4 ($p \leq .045$). In contrast, within the A group, trials 1, 2, 3, and 4 did not show significant differences from one another. The variable remained relatively stable upon the introduction of feedback. Interestingly, the pattern of the VA feedback group closely mirrors that of the A group, as confirmed by post-hoc tests.

4. Discussion

4.1. Effects on lane maintenance behaviour

The analyses presented in Section 3 highlight a significant effect of trial on all the analysed variables related to lane maintenance, with participants able to improve their performance in terms of ABSLP, SDLP, SDSTEER, and LATSPEED with respect to the baseline trial. The effect size of factor trial was large on SDLP, ABSLP and LATSPEED, and medium for SDSTEER.

This is a first expected yet notable finding, which, thanks to the expanded cohort of participants analysed here, confirms and strengthen the evidence of the overall effectiveness of this PT approach observed in past studies (Biondi et al., 2020; Rossi et al., 2022a, 2020a). In particular, the improvements are immediately evident in trial 2; the subsequent trials, conducted in the presence of feedback, yielded slight but significant additional improvements in ABSLP and SDLP, while no improvements were observed for SDSTEER and LATSPEED. This highlights the strength of a well-designed PT system, allowing participants to achieve a high level of task proficiency with relatively limited practice. Indeed, the absence of additional gains in subsequent trials can likely be attributed to floor effect, given the inherent challenge in further enhancing lane maintenance behaviour. Notably, these improvements are not attributable to learning/familiarization effects, as testified by the fact that a control group, driving four times on the same scenario without any feedback, showed no significant improvement (Biondi et al., 2020).[2]

These improvements, however, are reasonably partly caused by the fact that trials 2–4 introduced not only a feedback system but also the objective of improving lane maintenance. As discussed more extensively in Section 4.4, the study design does not allow us to isolate this effect.

It is also important to note, as anticipated in Section 2.7, that this task proficiency was always assessed with the feedback system active; the experiment did not investigate skill retention after feedback removal.

In terms of feedback type effect, the discussion of the results is less straightforward. The visual feedback was statistically more effective than the auditory feedback and marginally more effective than the visual/auditory feedback in correcting participants' lateral position (variable ABSLP). However, visual feedback was less effective compared to the other feedback systems on lateral control, when considering the SDLP variable. Also, notably, the effectiveness of the three systems tended to converge in trial 4 for ABSLP, whereas it tended to diverge for SDLP. The visual group effectively reached a plateau at a significantly higher level of SDLP compared to the others (Fig. 6a-b).

A plausible explanation for these divergent effects (on ABSLP and SDLP) is that participants were continuously stimulated by the visual feedback, prompting them to make ongoing adjustments to their lateral position. Conversely, since the auditory feedback was provided exclusively when participants entered or exited the correct area, participants in the auditory feedback group tended to intervene less frequently. Consequently, participants receiving the visual feedback were able to improve their lateral position more than those in the auditory-feedback group (ABSLP), albeit at the expense of overall lower lateral control (SDLP).

In summary, (i) all three feedback modalities proved effective in enhancing drivers' lane maintenance behaviour, and (ii) auditory and bimodal systems were more effective in improving SDLP compared to

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[2] Biondi et al. (2020) provided evidence only regarding SDLP, LP, and SDSTEER. We conducted additional analyses on the same control group, confirming that neither ABSLP nor LATSPEED changed across trials.

the visual system but less effective in enhancing ABSLP.

Interestingly, consistent with the findings of Biondi et al. (2020), the bimodal feedback demonstrated a similar level of effectiveness to auditory-only feedback, suggesting that when both modalities were present, participants prioritized the auditory aspect. This is likely because their visual attention was primarily directed toward the driving task.

4.2. Effects on other driving variables

Other variables, not directly connected to the feedback system, were analysed: SPEED and ACC. Both showed a tendency to decrease when the feedback system was active in comparison to the baseline trial (independently from the feedback type). This suggests that participants adopted a more cautious and smoother driving style, which can be attributed to their necessity to keep the vehicle within the correct area, a task facilitated by lower and consistent speeds. As for the lateral control variables discussed in Section 4.1, these changes are not related to learning/familiarization effects.[3]

However, it should be noted that SPEED significantly increased in trial 3 and 4 for the Visual feedback group, although this increase was rather small in absolute terms (about 0.9 m/s between trials 2 and 4, corresponding to a 4.5 % increment). This intriguing behavioural pattern could be attributed to two distinct explanations: the effectiveness of the visual feedback in enhancing drivers' lateral position (i) might have emboldened them to re-establish their usual speed while maintaining good performance; (ii) could mean a response to potential frustration with the feedback system, prompting participants to speed up in an attempt to expedite task completion. It is also plausible that a combination of these two elements played a role.

4.3. Practical implications

The findings of this study offer valuable practical insights. Firstly, it is crucial to emphasize that all the tested feedback systems led to substantial enhancements in participants' lane maintenance behaviour, confirming and strengthening the evidence regarding the potential usefulness of the PT technique for driver training.

Although visual feedback proved more effective in improving the mean lateral position, participants in the visual group exhibited an overall inferior level of lateral control. As previously discussed, this could be attributed to the visual feedback being intrusive due to its overlap with the visual stimuli relevant for the driving task and its continuous nature. Furthermore, it is possible that it led to some driver annoyance, as evidenced by the increase in average speed. As discussed in Section 4.1, this indicates that the visual modality, despite providing an overall positive impact on lane maintenance, seems to be the least suitable among the three in practical terms.

Considering that the combination of visual and auditory cues yielded results quite similar to those of auditory-only feedback, the latter holds the most promise in practical applications. This is because it introduces less interference with other stimuli that drivers might encounter on the road.

It is important to note that the current system was designed for offline driving-simulator-based training. This system could be beneficial for educating novice drivers or retraining experienced drivers (e.g., professional drivers or drivers who lost their license) in maintaining correct lateral control and position. The PT protocol could also be adapted to train other, even more complex driving skills. The "reach" that a simulation-based training tool can have in terms of practical implementation strongly depends on policy decisions, which could consider making such training sessions an integral part of the process required to obtain a driving license or professional certifications. Of course, as discussed in Section 4.4, further testing is necessary to evaluate not only learning retention but also learning transferability to on-road driving. However, if the effectiveness is confirmed, this could be a viable driving education tool, able to provide results with limited time and budget in a completely safe environment.

Another path for future development is a direct application to on-road driving after an appropriate adaptation of the current system. While it is impractical to apply the visual or bimodal feedback to real-world onboard training due to their intrusiveness, potentially leading to mental overload when exposed to real-world driving stimuli, the auditory system presented here could be a viable tool for such training, with potential adjustments to further reduce its impact on drivers' workload, and avoid disturbance/distracting effects (Biondi et al., 2014).

4.4. Limitations

There are some limitations to this study that are worth mentioning and that future research will address.

Firstly, the slightly lower effectiveness of visual feedback compared to other modalities is attributed here to a likely excessive intrusiveness. However, this hypothesis lacks unequivocal empirical evidence, and this could be obtained for instance by replicating the experiment with the use of an eye-tracking device. Future research could also explore alternative types and positions of visual stimuli, possibly operating in a non-continuous manner.

Secondly, regarding auditory feedback, it will be necessary to explore and test various features of the sounds used, with the ultimate goal of adapting the system for on-road training while maintaining its effectiveness. Particular attention will be given to avoiding potential negative disturbance effects, such as drivers being startled and momentarily experiencing a reduction in lateral control (Biondi et al., 2014).

Thirdly, the study did not examine the potential application of haptic feedback systems. This is primarily due to the slower response to haptic signals, which may require higher intensity for detection (Spence and Gallace, 2007), potentially limiting real-world applications. However, future research should aim to provide further evidence on this and even consider testing combinations of haptic and auditory stimuli within a PT driving training protocol.

Fourthly, in this study, after the baseline in which participants were instructed to drive naturally, trials 2–4 were carried out not only with the addition of a feedback system but also with the objective of improving lane maintenance. Although this designed was chosen so as to align with a PT protocol (see Section 2.7), it is also true that it does not allow us to separate the contributions of the "objective" and "feedback" effects. We have no reason to believe that the "objective" effect might have different impacts with different feedback types, and therefore, it should not affect the overall findings of this paper. Nevertheless, it would have been valuable to compare these results to those of another experimental group in which participants were exposed a non-PT protocol, consisting of simply being instructed to maintain a certain lateral position/control.

Lastly, while past research on a limited number of participants has shown that the effects of auditory and bimodal feedback persist over time in laboratory conditions (Rossi et al., 2022a), a more structured and larger-scale experiment will be needed to more robustly assess the retention of the skills acquired with this kind of PT protocol. Furthermore, it is also essential to assess the extent to which these abilities are retained by participants while driving in real-world conditions. This evaluation is crucial to determine the viability of the PT technique for offline training. It is important to remember that the limitations of a laboratory setting play a critical role. In the laboratory, control over

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[3] Investigation on longitudinal control variables for the control group was not reported in Biondi et al. (2020). Similarly to lateral control variables, no significant effect of learning/familiarisation across trials was observed either for SPEED or ACC in the control group.

auditory and visual sensory channels can be more effectively maintained compared to on-road experiments, where drivers face numerous and simultaneous external stimuli, often unexpected. These external stimuli may divert the driver's attention away from the warning feedback, potentially leading to overlook it. Therefore, after testing and validating a feedback system in laboratory conditions, as we did here, it becomes imperative to conduct additional research directly on the road, which will allow for its practical implementation in the real world. Regarding replication in on-road conditions, it is not known whether the findings for this group of participants may effectively generalize to novice drivers, very experienced drivers, or drivers identified for re-education. Therefore, replicating the test on a diverse cohort of drivers is recommended.

5. Conclusion

This study conducted a comprehensive investigation and comparison of different feedback systems within the context of a Precision Teaching approach aimed at improving lane maintenance. The research employed a driving simulator experiment to assess the effectiveness of visual, auditory, and bimodal visual-auditory feedback systems. Expanding on our prior work (Biondi et al., 2020), the study involved the recruitment of additional participants and introduced a new experimental group. The primary objective was to determine which modality proved most effective and practical. This question, which remains largely unanswered in the published literature on the topic, was previously left open in our earlier work.

The main findings can be summarized as follows:

The tested systems significantly improved the lane maintenance behaviour of participants. Notably, improvements were already evident after the first trial run with feedback, and subsequent trials exhibited marginal further progress. These results underline and reaffirm the potential of the PT technique in the domain of driver training, previously reported in Biondi et al. (2020), Rossi et al. (2022a, 2022b).

Both auditory and bimodal systems yielded the most favourable outcomes in terms of lateral control, proving more effective in reducing SDLP. No significant distinctions between these two systems were observed.

Despite its effectiveness in terms of ABSLP improvement, the visual feedback raised concerns due to the conspicuous increase in SPEED observed across trials.

Beyond the enhancement of lane maintenance, participants exhibited a more cautious and smooth driving style when driving with active feedback, as evidenced by the overall reduction in speed and acceleration values.

With regard to the hypotheses outlined in Section 1, this study contributed to providing several valuable insights that can be used to guide future research a practical application. It must be noted that, all three tested modalities demonstrated general effectiveness, and a clear-cut, most effective modality did not unequivocally emerge. In this sense, the first research hypothesis was only partially met, as the visual feedback was shown to be the least adequate for just one of lane maintenance variables investigated, i.e. SDLP. The second research hypothesis was confirmed and positive indirect improvements in longitudinal control were observed.

As discussed in Section 4, auditory and bimodal modalities yielded very similar results and, significantly, provided positive and enduring effects on all investigated variables. While the visual modality proved most effective in terms of lateral position, it was less suitable for overall lane maintenance due to its comparatively lower effectiveness in lateral control improvement and potential adverse effects on drivers' speed. This was likely caused by an excessive intrusiveness as it operated continuously and possibly overlapped with other visual stimuli encountered by participants while driving.

Considering that the PT technique can be utilized not only for offline (in a controlled laboratory environment) training, but also for online (on the road) training, the auditory system appears more feasible for implementation in real-world vehicles. This consideration takes into account technological aspects as well as the fact that it has fewer overlaps with other information (typically more visual than auditory) that drivers need to process while driving.

Based on these considerations, although all three modalities exhibit general effectiveness, the auditory modality emerges as the most suitable for practical applications. It demonstrates comparable or slightly superior effectiveness compared to the others while being less intrusive and more feasible for on-road training.

As research on the application of PT protocols in the field of driving training is still in its early stages, several potential research directions could be pursued in the future to address certain limitations of the present study.

CRediT authorship contribution statement

Mariaelena Tagliabue: Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Giulia De Cet:** Writing – original draft, Investigation, Formal analysis, Data curation. **Federico Orsini:** Writing – review & editing, Writing – original draft, Software, Investigation. **Massimiliano Gastaldi:** Writing – review & editing, Supervision, Methodology. **Riccardo Rossi:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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