The Effect of Concurrent Bandwidth Feedback on Learning the Lane-Keeping Task in a Driving Simulator

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Objective: The aim of this study was to investigate whether concurrent bandwidth feedback improves learning of the lane-keeping task in a driving simulator.

Background: Previous research suggests that bandwidth feedback improves learning and that off-target feedback is superior to on-target feedback. This study aimed to extend these findings for the lane-keeping task.

Method: Participants without a driver's license drove five 8-min lane-keeping sessions in a driver training simulator: three practice sessions, an immediate retention session, and a delayed retention session 1 day later. There were four experimental groups (n = 15 per group): (a) on-target, receiving seat vibrations when the center of the car was within 0.5 m of the lane center; (b) off-target, receiving seat vibrations when the center of the car was more than 0.5 m away from the lane center; (c) control, receiving no vibrations; and (d) realistic, receiving seat vibrations depending on engine speed. During retention, all groups were provided with the realistic vibrations.

Results: During practice, on-target and off-target groups had better lane-keeping performance than the nonaugmented groups, but this difference diminished in the retention phase. Furthermore, during late practice and retention, the off-target group outperformed the on-target group. The off-target group had a higher rate of steering reversal and higher steering entropy than the nonaugmented groups, whereas no clear group differences were found regarding mean speed, mental workload, or self-reported measures.

Conclusion: Off-target feedback is superior to on-target feedback for learning the lane-keeping task.

Application: This research provides knowledge to researchers and designers of training systems about the value of feedback in simulator-based training of vehicular control.

Keywords: augmented feedback, off- and on-target feedback, tracking task, driver training, skill development, tactile display

INTRODUCTION

Augmented feedback—that is, feedback other than the naturally available task-intrinsic feedback—is an important component of driver training. For example, learners may receive feedback on performance from a driving instructor (Hatakka et al., 2003) or automatically from a computer in case of simulator-based training (De Groot, De Winter, Mulder, & Wieringa, 2007). Nowadays, an estimated 150 driving simulators are used by driving schools in the Netherlands for basic driver training (SWOV Institute for Road Safety Research, 2010). Augmented feedback is a new trend in simulator-based driver training of tracking tasks, such as lane keeping and car following (Bekiaris, 2007).

Augmented feedback usually facilitates performance when provided during practice. However, it can have a negative impact on learning performance as measured during posttraining retention sessions without augmented feedback (Salmoni, Schmidt, & Walter, 1984; Schmidt & Wulf, 1997). For effective learning, augmented feedback should be provided sparingly and in such a way that the learner does not become dependent on it (see Swinnen, 1996, for a review). One possible way to accomplish this is to provide bandwidth feedback, which is feedback that depends on whether performance is within or outside a preset tolerance limit.

Bandwidth feedback has a long history starting with Thorndike's (1927) experiments in which participants received verbal right-wrong feedback after estimating the lengths of paper strips or drawing lines of particular lengths. Bandwidth feedback has also been used as concurrent feedback during tracking tasks. For example, Reynolds and Adams (1953) found that providing participants with an auditory click whenever on-target on a rotor pursuit task improved performance and learning (for reviews on motor learning, see Adams, 1964; Bilodeau & Bilodeau, 1961). With few exceptions, these early studies provided the augmented feedback when performance was on-target. Feedback was seen as a
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means of reinforcing habits and for providing motivation to learn. More recent studies used off-target feedback, providing the augmenting cues when performance deviated outside the tolerance limit (Goodwin & Meeuwsen, 1995; Lai & Shea, 1999; T. D. Lee & Carnahan, 1990; T. D. Lee & Maraj, 1994; Lintern, 1980; Reeve, Dornier, & Weeks, 1990; Sherwood, 1988; Smith, Taylor, & Withers, 1997).

One can argue whether on- or off-target feedback is most effective (Swinnen, 1996). On-target feedback may be more rewarding and stimulating for the learner. Off-target feedback, on the other hand, is less likely to distract the learner or make the learner dependent on the feedback, as no supplementary cues are provided when performing within reasonable standards (Lintern, 1991; Swinnen, 1996).

Only three studies could be found which made a direct comparison between on- and off-target feedback. Williams and Briggs (1962) let participants track a sinusoidal signal via a one-dimensional compensatory display. Augmented feedback was provided by means of auditory clicks when the participant was within or outside tolerance limits. During practice and immediate retention sessions without augmented feedback, the off-target group outperformed the on-target group, which in turn performed better than a control group not receiving augmented feedback during practice. A later study by Gordon and Gottlieb (1967) used a rotor pursuit task with visual augmented feedback from a lightbulb. The on- and off-target groups outperformed the control group during practice and retention, with a slight and insignificant superiority for the off-target group. A more recent study by Cauraugh, Chen, and Radlo (1993) compared the effects of on- and off-target knowledge-of-results feedback on learning a 500-ms timing task. The reported effects were again in favor of off-target feedback, albeit not statistically significant. In summary, off-target feedback seems to be more effective than on-target feedback, although the reported effects are not uniformly supportive.

This study focuses on lane keeping, which is a fundamental control task that drivers should master to drive safely. Crashes in traffic are not usually the result of adverse perceptual motor skills of lane keeping per se but are generally the consequence of a complex interplay of events, including, for example, inattention lapses and intentional violations. Nonetheless, lane-keeping performance has been associated with driver impairment and has been used as a proxy variable for road safety in numerous studies (e.g., Brookhuis & De Waard, 1993; Ranney, Harbluk, & Noy, 2005; Verster, Veldhuijzen, Patat, Olivier, & Volkerts, 2006).

Our aim was to compare the effects of on-target versus off-target feedback for learning the lane-keeping task in a driving simulator. We investigated concurrent feedback: a nondirectional seat vibration indicating in real time whether the center of the car was inside or outside an invisible 1-m-wide band during practice sessions. The lane-keeping task features clear intrinsic feedback, which reduces the risk of learners becoming dependent on augmenting cues (cf. Kinkade, 1963). We chose vibrotactile augmented feedback to minimize interference with the visual driving task. Vibrotactile feedback has been used for effective presentation of in-vehicle warning and navigation signals (Ho, Reed, & Spence, 2007; Jones & Sarter, 2008; J. D. Lee, Hoffman, & Hayes, 2004; Suzuki & Jansson, 2003; Van Erp & Van Veen, 2004).

After three practice sessions, learning performance was assessed during an immediate retention session and a 1-day delayed retention session, considering the role of sleep in performance consolidation (Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002). Earlier research has indicated that information-processing abilities and mental effort have an important influence on learning (Ackerman, 1987; Guadagnoli & Lee, 2004; T. D. Lee, Swinnen, & Serrien, 1994). Therefore, we measured these constructs using a secondary task and a questionnaire.

METHOD

Participants

We recruited 60 persons without a driver’s license from the Delft University of Technology student community. The participants completed an intake questionnaire with the following items: (a) gender (male or female), (b) age, (c) “Did you take driving lesson(s) on the road?” (yes or no), (d) “Have you ever driven in a simulator before?”

METHOD
(yes or no), (e) “Do you play video games for at least 1 hour per week?” (yes or no), and (f) “I have good steering skills (for example in cycling or computer games)” (on a 10-point scale from 1 = completely disagree to 10 = completely agree).

Earlier research suggested that these items are predictive of lane-keeping performance in a simulator (Backlund, Engström, Johannesson, & Lebram, 2010; De Winter et al., 2006, 2009). Of the 60 participants, 13 were female, 23 had started taking driving lessons on the road, 6 had driven in a simulator before, and 31 reported playing video games for more than 1 hr per week. The mean age was 19.7 years (SD = 2.3), and the mean self-reported steering skill was 6.8 (SD = 1.6).

**Apparatus**

The driving simulator (Figure 1) was fixed base and provided a realistic simulation of a middle-class passenger car with 180° field of view and surround sound. This simulator is used for initial driver training in the Netherlands (Green Dino, Wageningen, Netherlands). The pedals, steering wheel, ignition key, and seat resembled those of an actual car, and gear changing was automatic. The steering wheel provided force feedback using a DC torque motor coupled to the steering shaft through an 8:1 gearbox (Dunkermotoren, Bonndorf, Germany). The applied torque was a function of the speed and steering wheel angle from the car model, representing static friction and aligning torque.

The virtual world was projected by means of three LCD projectors (front projector NEC VT676, brightness 2,100 ANSI lumens, contrast ratio 400:1, resolution 1,024 × 768 pixels; side projectors NEC VT470, brightness 2,000 ANSI lumens, contrast ratio 400:1, resolution 800 × 600 pixels), and the dashboard, interior, and mirrors were integrated in the projected image. Vibrations were provided by a tactile transducer (ShakerCentre, Brentwood, UK) fixed vertically onto the metal frame of the seat.

**Experimental Groups**

There were four experimental groups: on-target, off-target, control, and realistic (n = 15 per group). Assignment of a new participant to one of the four groups was determined so as to minimize the differences between the groups in terms of number of women and mean age.

The on-target and off-target groups practiced with concurrent vibratory bandwidth feedback. For the on-target group, the vibration automatically switched on when the center of the car was within 0.5 m of the center of the lane. For the off-target group, the vibration was operative when the center of the car was more than 0.5 m away from the lane center.

The vibrations applied for the on-target and off-target groups had a frequency of 100 Hz and a constant intensity of 0.09 m/s² root mean squared (RMS), values chosen subjectively by the experimenters so that the vibrations were clearly perceivable but not annoying. The vibration intensity was measured during pilot sessions with a vertical accelerometer sampled at 200 Hz, positioned on the seat cushion with a human sitting on top. Note that the augmented feedback was nondirectional; it indicated whether the participant was on-target or off-target, not whether left or right steering was required. The control group received no vibration feedback during practice. Participants in the realistic condition drove with vibrations depending on the speed of the simulated engine. The realistic vibrations represented a combination of the first- and second-order vibration modes of a four-cylinder engine. The vibration intensity varied between 0.06 m/s² and 0.12 m/s² RMS.

As a comparison, we measured RMS acceleration in a car with diesel engine while standing still and varying engine speed between 1,000 rpm...
and 3,500 rpm. The obtained RMS values were in approximately the same range (0.04 m/s² to 0.12 m/s²). Paddan and Griffin (2002) measured RMS on the seats of 25 cars traveling at different speeds on tarmac and concrete. The RMS ranged between 0.16 m/s² and 0.78 m/s². Pielmeier, Jeyabalan, Meier, and Otto (1997) measured just noticeable differences for three trained persons exposed to vibrations on a car seat. For a reference vibration of 0.08 m/s² RMS, perceptual thresholds ranged between 0.006 m/s² and 0.018 m/s². The realistic vibrations were therefore clearly perceivable and corresponded to those in a real car.

Procedure and Tasks

After recruitment, an e-mail was sent to the participants containing the time and location of the experiment as well as a protocol explaining that the task goal was to drive perfectly in the center of the right lane. All participants signed an informed consent form.

Participants first performed an 8-min baseline session in the simulator to practice the auditory reaction time task (described in this section). Next, five 8-min driving sessions were completed: three practice sessions, an immediate retention session, and a delayed retention session on the following day. In the retention phase, all participants were provided with the realistic vibrations. In other words, on-target, off-target, and control groups transferred to a higher-fidelity configuration, whereas the realistic group was provided with the same vibrations during practice and retention.

All driving sessions took place on a two-lane 7.5-km lap in a country environment without intersections or other vehicles. The lap consisted of 18 right and 20 left curves of varying angles and radii for which braking was needed. The lane width was 5 m. The road contained a tunnel and two 4-m hills. The road surface was uniform and flat; there was no horizontal curvature of the road profile as can be found in other simulators (Allen et al., 1999). Like in a real car, small steering corrections were continuously needed on the straights to keep the car in the center of the lane. Previous research on this simulator showed that performance on lane-keeping and steering tasks predicted the chance of passing the Dutch driving license test (De Winter et al., 2009).

Before each driving session, a series of textual instructions were projected in the simulator, explaining how to obtain a proper seating position, how to perform the reaction time task, how to control the car (steering wheel, throttle, and brake pedals), and, finally, the goal of the task (to drive in the center of the lane) and (only when appropriate) how to interpret the augmented feedback.

During both the baseline session and the five driving sessions, an auditory reaction time task had to be performed. Earlier driving simulator research demonstrated that reaction time tasks were sensitive in detecting differences in workload as a function of tactile feedback during car following (Mulder et al., 2004) and complexity of the driving context (Cantin, Lavallière, Simoneau, & Teasdale, 2009). The task was to react as quickly as possible to a 0.1-s beeping sound produced at a random time interval between 4 s and 8 s. The reaction time was measured from the moment the beep was produced until the moment the participant pressed the horn (central piece on the steering wheel). After pressing the horn, a second beep, with lower tone, was produced as a confirmation. No confirmation sound was produced when the participant did not react within 2 s. After each of the six sessions, participants were asked to step out of the simulator to complete the Rating Scale Mental Effort (Zijlstra, 1993).

Dependent Measures

The following dependent measures were calculated for each practice and retention session.

Percentage on-target. This variable was the percentage of driving time that the center of the vehicle was within 0.5 m of the center of the right lane of the two-lane road. Percentage on-target was our primary performance measure, as it reflects the behavior that was trained with the bandwidth feedback. It was also used in the seminal articles on off-target versus on-target feedback (Gordon & Gottlieb, 1967; Williams & Briggs, 1962). Data from 10 s prior to 20 s after a road departure were excluded for calculating percentage on-target, mean speed, steering reversal rate, steering entropy, and root mean squared error (RMSE) lane center.
Mean speed. This variable was mean speed of the simulated vehicle. Mean speed is an indicator of the participant's efficiency of proceeding along the course.

Number of departures. This variable measured the number of occasions that the vehicle was outside the lane boundaries with all its edges. The distance of the center of the vehicle to the center of the right lane was dependent on the heading of the vehicle and was on average 3.93 m (SD = 0.36 m) and 9.27 m (SD = 0.46 m) for departures to the right and to the left, respectively. Road departures were typically the consequence of improper lane-keeping behavior or loss of control because of approaching a curve too fast. When a road departure occurred, the participant was automatically placed back on the center of the right lane with zero speed.

Steering reversal rate. The number of steering wheel reversals per second is a measure of control activity that does not necessarily correlate with absolute measures of lane-keeping performance (McLean & Hoffmann, 1975). A high steering reversal rate indicates that the driver made many steering corrections and gave high-frequent steering wheel input. A reversal was defined as a change from a clockwise movement to a counterclockwise movement, provided that the counterclockwise steering velocity exceeded 3.0 deg/s (Theeuwes, Alferdinck, & Perel, 2002). Previous research has shown that the steering reversal rate is sensitive to changes in task demand and control effort, albeit in a complex manner (MacDonald & Hoffmann, 1980).

Steering entropy. Steering entropy, representing the information content and smoothness of the steering wheel angle, was calculated as described by Nakayama, Futami, Nakamura, and Boer (1999), except that a 4-Hz instead of a 7-Hz resample frequency was applied. This modification was recommended by Boer, Rakauskas, Ward, and Goodrich (2005) to make the entropy measure more sensitive to changes of the driving task. The bin width was set at 2.15°, representing 60% of the frequency distribution of the prediction error averaged across all sessions and participants (60% was also taken from Boer et al., 2005). High steering entropy means that the driver’s steering wheel input was discontinuous and irregular.

RMSE lane center. This variable refers to the RMSE of the distance of the center of the vehicle to the center of the right lane. It describes how accurately the driver kept the vehicle near the lane center but in a way that is more remotely related to the bandwidth feedback than percentage on-target.

Mean reaction time. The mean reaction time on the auditory reaction time task, representing the participant’s mental workload, was also calculated. Reaction times less than 0.15 s (anticipatory responses or “false alarms”) and reaction times exceeding 2 s (missed responses) were excluded.

Effort. The Rating Scale Mental Effort provides an indication of the participant’s level of effort expenditure (Zijlstra, 1993). This rating scale was presented on an A4 paper with a 150-mm vertical bar with anchors every nine points from 2 mm (absolutely no effort) to 112 mm (extreme effort). The instructions on the form stated, “Please indicate, by marking the vertical axis below, how much effort it took for you to complete the task you have just finished.”

After finishing the delayed retention task, participants completed a 14-item questionnaire. The items represented statements to be answered on a scale from 1 (completely disagree) to 10 (completely agree) concerning the participant’s enjoyment, task difficulty, simulator sickness, concentration, realism of the simulator, the ability to judge speed and distance, and the need for feedback about task performance. In this study, we were interested in the response to the statement “Keeping the car in the center of the lane was easy” as an indicator of workload. The obtained scores were reversed so that a score of 1 corresponded to easy and a score of 10 corresponded to difficult.

Statistical Analyses

Comparisons between groups were conducted using a full-factorial analysis of covariance (ANCOVA). ANCOVA was performed for the four groups together and for the following four group pairs: on-target versus the nonaugmented groups (control and realistic combined), off-target versus the nonaugmented groups, on-target versus off-target, and control versus realistic. F statistics comparing group pairs were converted to
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Cohen’s $d$ (i.e., the standardized mean difference) for ease of interpretation, as $d$ conveys information about the sign and size of the effect independent of the sample size.

Comparisons between sessions were carried out with repeated-measures ANCOVA. To assess changes during practice, Practice 1 and Practice 3 were included as within-subjects variables. To assess changes from practice to retention, Practice 3 and delayed retention were included as within-subjects variables.

The covariate used in ANCOVA was the participants’ initial aptitude. This variable was calculated from the following information acquired prior to commencing the first practice session: the six items from the intake questionnaire and the mean reaction time and effort of the baseline session. The matrix of these variables (60 participants × 8 variables) was reduced into one score, representing the initial aptitude, by taking the first principal component based on the correlation matrix. The mean initial aptitude scores were .05, −.28, .19, and .04 for on-target, off-target, control, and realistic groups, respectively. These means were not significantly different as determined with a one-way ANOVA ($F = 0.57$, $p = .640$).

RESULTS

An investigation of the normal probability plots showed that the number of departures had a considerably skewed distribution. Therefore, a square root transformation was applied on this measure. The correlation matrix in Table 1 shows that the percentage on-target, the number of departures, and RMSE lane center were substantially correlated, as these are all measures of lane-keeping performance. Furthermore, steering reversal rate and steering entropy turned out to be strongly correlated (.92), which implies that these variables essentially describe the same construct.

A low reversal rate and low entropy are indicative of “smoothness of control” (e.g., Nakayama et al., 1999, p. 2). The initial aptitude covariate was significantly predictive of five of the nine dependent measures. The reliabilities, shown on the diagonal of Table 1, were mostly above .8 and were considered adequate for ergonomics research (cf. Liu & Salvendy, 2009). The number of departures had a relatively low reliability (.56), which implies that significant effects are less likely for this measure. The low reliability can be explained by the fact that departures were relatively infrequent events, with 32%, 67%, 68%, 80%, and 75% of the participants having no departures during the five respective driving sessions.

Table 2 shows the uncorrected means and standard deviations of the dependent measures per group and session, Table 3 shows the group effects and the within-subjects effects of the four
groups together, and Table 4 shows the results of the comparisons between group pairs.

**Percentage on-target.** During practice, on-target and off-target groups drove a significantly larger percentage of the time on the lane center target than the nonaugmented groups. For on-target drivers, this advantage disappeared in the retention phase. For off-target drivers, much of the advantage remained during immediate retention, although a clear drop in performance was evident during delayed retention. The differences between off-target
and the nonaugmented groups were $d = 1.01$ ($p = .002$) and $d = 0.58$ ($p = .069$) during immediate and delayed retention, respectively, which classify as moderate to strong effects (Cohen, 1988).

As expected, drivers in the off-target condition outperformed those in the on-target condition. This difference was not apparent during Practice 1 but appeared in Practice 2, reached significance in Practice 3, and persisted during immediate and delayed retention. There was no significant difference between control and realistic groups. Percentage on-target increased for all groups during practice, a strong effect clearly illustrated in Figure 2. The groups driving without augmented feedback continued to improve from Practice 3 to delayed retention, $F(1, 27) = 11.5$, $p = .002$, whereas the performance of the augmented feedback groups deteriorated, $F(1, 27) = 7.10$, $p = .008$.

**Mean speed.** There were no significant group differences during practice or retention concerning the mean speed. Table 3 shows that there were no significant differences between Practice 1 and 3 or between Practice 3 and delayed retention. Nonetheless, there were significant differences between the sessions when considering the five sessions combined, $F(4, 220) = 3.29$, $p = .012$. A post hoc analysis indicated that the speed during Practice 2 was significantly slower than during Practice 1, Practice 3, and delayed retention. Furthermore, participants drove significantly faster during delayed retention as compared with immediate retention. As can be seen in Table 2, the effects were small on an absolute scale: All mean speeds of the 20 combinations of session and group ranged between 15.4 m/s and 16.7 m/s.

**Number of departures.** No significant group differences for the number of road departures were found. Control and off-target groups had a slightly elevated number of departures during immediate retention, a statistically insignificant effect. The number of departures decreased from Practice 1 to Practice 3 but did not decrease significantly from Practice 3 to delayed retention.

**Steering reversal rate and steering entropy.** The results in Table 3 show that participants’ steering became significantly smoother from Practice 1 to Practice 3. Table 4 shows that drivers in the off-target condition had less smoothness of control (i.e., higher reversal rate and entropy) than the nonaugmented groups during practice and retention with all $p$ values below .05, except for steering entropy during retention. The results for the steering reversal rate are illustrated in Figure 3.

**RMSE lane center.** This measure correlated strongly with the number of departures and percentage on-target. RMSE lane center strongly

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**TABLE 3: Group Effects and Within-Subjects Effects**

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Practice 1 vs. Practice 3</th>
<th>Practice 1 vs. Delayed Retention</th>
<th>Practice 3 vs. Delayed Retention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage on-target</td>
<td>8.70 (.000)</td>
<td>4.18 (.010)</td>
<td>1.87 (.145)</td>
</tr>
<tr>
<td>Mean speed</td>
<td>0.29 (.830)</td>
<td>1.06 (.374)</td>
<td>0.18 (.911)</td>
</tr>
<tr>
<td>Number of departures</td>
<td>0.05 (.984)</td>
<td>1.72 (.173)</td>
<td>0.70 (.555)</td>
</tr>
<tr>
<td>Steering reversal rate</td>
<td>2.63 (.059)</td>
<td>2.22 (.096)</td>
<td>2.63 (.059)</td>
</tr>
<tr>
<td>Steering entropy</td>
<td>2.50 (.069)</td>
<td>1.09 (.361)</td>
<td>0.88 (.457)</td>
</tr>
<tr>
<td>RMSE lane center</td>
<td>2.52 (.068)</td>
<td>1.91 (.138)</td>
<td>0.97 (.412)</td>
</tr>
<tr>
<td>Mean reaction time</td>
<td>0.38 (.766)</td>
<td>0.82 (.490)</td>
<td>0.11 (.956)</td>
</tr>
<tr>
<td>Effort</td>
<td>1.39 (.257)</td>
<td>1.12 (.348)</td>
<td>1.64 (.190)</td>
</tr>
</tbody>
</table>

*Note. F values are shown with $p$ values in parentheses. RMSE = root mean squared error.
*There was a significant Session × Group interaction, $F(3, 55) = 5.35$, $p = .003$. 

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improved with practice. The same trends between groups were found as for percentage on-target, albeit with weaker effects.

**Mean reaction time.** There were no significant group differences, but there was a clear learning effect: The reaction time decreased from Practice 1 to Practice 3 and decreased further from Practice 3 to delayed retention.

**Effort.** No significant group differences were found. Drivers in the control group tended to report higher effort than those in the realistic condition. There was a clear learning effect: Participants provided lower effort ratings for Practice 3 as compared with Practice 1 and tended to further reduce effort from Practice 3 to delayed retention.

### TABLE 4: Comparisons Between Group Pairs (Cohen’s d)

<table>
<thead>
<tr>
<th>Group Pair</th>
<th>Practice</th>
<th>Retention</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>On-target (n = 15) vs. nonaugmented (n = 30)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percentage on-target</td>
<td>1.00**</td>
<td>0.81*</td>
</tr>
<tr>
<td>Mean speed</td>
<td>0.10</td>
<td>−0.21</td>
</tr>
<tr>
<td>Number of departures</td>
<td>0.08</td>
<td>−0.17</td>
</tr>
<tr>
<td>Steering reversal rate</td>
<td>0.10</td>
<td>−0.02</td>
</tr>
<tr>
<td>Steering entropy</td>
<td>0.30</td>
<td>0.16</td>
</tr>
<tr>
<td>RMSE lane center</td>
<td>−0.45</td>
<td>−0.29</td>
</tr>
<tr>
<td>Mean reaction time</td>
<td>−0.14</td>
<td>−0.07</td>
</tr>
<tr>
<td>Effort</td>
<td>−0.12</td>
<td>−0.12</td>
</tr>
</tbody>
</table>

| Off-target (n = 15) vs. nonaugmented (n = 30) |          |           |           |           |           |
| Percentage on-target | 0.97**   | 1.23***   | 1.54***   | 1.01**    | 0.58#     |
| Mean speed | 0.36     | 0.05      | −0.13     | −0.30     | −0.20     |
| Number of departures | −0.14    | 0.14      | −0.10     | −0.03     | 0.15      |
| Steering reversal rate | 0.81*    | 0.66*     | 0.94**    | 0.81*     | 0.84**    |
| Steering entropy | 0.94**   | 0.63*     | 0.76*     | 0.55#     | 0.53#     |
| RMSE lane center | −0.53#   | −0.85**   | −0.90**   | −0.63*    | −0.37     |
| Mean reaction time | 0.16     | 0.38      | 0.34      | 0.47      | 0.17      |
| Effort | −0.24    | −0.27     | −0.20     | −0.20     | 0.04      |

| Off-target (n = 15) vs. on-target (n = 15) |          |           |           |           |           |
| Percentage on-target | 0.11     | 0.65      | 0.98*     | 0.90*     | 0.88*     |
| Mean speed | 0.25     | 0.29      | 0.50      | 0.21      | −0.06     |
| Number of departures | −0.23    | 0.31      | 0.01      | 0.54      | 0.16      |
| Steering reversal rate | 0.77#    | 0.81*     | 0.51      | 0.41      | 0.32      |
| Steering entropy | 0.54     | 0.53      | 0.50      | 0.31      | 0.17      |
| RMSE lane center | −0.13    | −0.59     | −0.73#    | −0.90*    | −0.50     |
| Mean reaction time | 0.31     | 0.48      | 0.17      | 0.30      | 0.08      |
| Effort | −0.14    | −0.21     | −0.22     | −0.44     | −0.09     |

| Realistic (n = 15) vs. control (n = 15) |          |           |           |           |           |
| Percentage on-target | 0.05     | 0.20      | 0.14      | 0.05      | 0.06      |
| Mean speed | 0.12     | −0.03     | −0.13     | −0.55     | −0.22     |
| Number of departures | −0.26    | 0.26      | 0.01      | −0.55     | 0.55      |
| Steering reversal rate | 0.32     | 0.49      | 0.23      | 0.28      | 0.42      |
| Steering entropy | 0.54     | 0.36      | 0.27      | 0.19      | 0.18      |
| RMSE lane center | 0.37     | 0.03      | 0.16      | −0.22     | 0.44      |
| Mean reaction time | −0.07    | 0.07      | 0.27      | 0.04      | 0.00      |
| Effort | −0.74#   | −0.58     | −0.74#    | −0.56     | −0.93*    |

Note. RMSE = root mean squared error.
*p < .1. *p < .05. **p < .01. ***p < .001.
ANCOVA performed on each of the 14 post-experiment questions separately revealed not one significant difference between the four groups. The marginal means of the task difficulty scores were 5.2, 5.2, 5.2, and 4.4 on a scale from 1 to 10 for on-target, off-target, control, and realistic groups, respectively ($F = 0.910, p = .442$).

**DISCUSSION**

This study investigated the potential of concurrent vibratory bandwidth feedback for learning the lane-keeping task in a driving simulator. The on-target and off-target groups outperformed the control and realistic groups during practice and immediate retention, but consistent with the guidance hypothesis (Salmoni et al., 1984), performance of the augmented-feedback groups deteriorated during retention. The most significant finding of this research is that performance of drivers in the off-target condition was superior to that of drivers in the on-target condition during practice and retention. This replicates the early work of Williams and Briggs (1962) for an ecologically valid task. No clear group differences were found regarding mean speed, mental workload, or self-reported measures.

Literature describes three possible reasons that off-target feedback may be superior to on-target feedback. First, off-target feedback is sensitive to the needs of the learner because the amount of feedback is smaller for the better skilled drivers and reduces when performance improves (T. D. Lee et al., 1994). Williams and Briggs (1962) used a similar argumentation to explain why the off-target group performed better than the on-target group during retention trials: “This is logical in view of the similarity between the training and transfer trials for the off-target group; during training these subjects experienced a diminution in number of auditory clicks as result of increasing skill” (p. 524). Indeed, during Practice 1, on-target and off-target groups on average received vibrations 66% and 33% of the time, respectively; during Practice 3, this difference had grown to 73% and 18%, respectively.

A second reason drivers receiving on-target feedback underperformed may be that because the augmented feedback is provided when they are within the tolerance limit, it blocks processing of intrinsic visual feedback (Lintern, 1980). Off-target feedback, on the other hand, does not distract from intrinsic feedback sources and does not permit the learner to become dependent on the augmented feedback.

A third advantage of off-target feedback may be that it stimulates the learner to correct performance only when errors are large, preventing maladaptive short-term corrections beyond the precision of the motor system (T. D. Lee & Carnahan, 1990; Sherwood, 1988). However, these reasons cannot satisfactorily explain the superior retention performance of the off-target group, because on-target and off-target groups in essence used an identical on-off feedback algorithm, switching sign on bandwidth crossings; only the sign of the feedback was opposite. Because of the identical algorithm, there

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**Figure 2.** Estimated marginal means of the percentage on-target for the four experimental groups during practice and retention. Estimated marginal means are the predicted means when holding the initial aptitude covariate at its mean value of zero.

**Figure 3.** Steering reversal rate for the four experimental groups during practice and retention. Estimated marginal means are the predicted means when holding the initial aptitude covariate at its mean value of zero.
was no apparent reason why learners should become more dependent on on-target feedback any more than on off-target feedback. Furthermore, our comparison between realistic and control groups showed that vibrations per se did not have a negative effect on practice and retention performance (for discussion on the effect of disturbance motion cues, see Caro, 1979). Moreover, both on-target and off-target groups transferred to a new condition (the realistic vibrations), so drivers receiving off-target feedback were not more familiar with the retention condition than those receiving on-target feedback.

We conducted a supplementary analysis of steering correction behavior. In the practice phase, and particularly during Practice 3, drivers in the off-target group drove on average shorter periods outside the bandwidth than those in the on-target group ($M = 1.78$ s vs. $M = 2.28$ s, $p = 0.011$, $d = −1.04$), who in turn drove shorter periods outside the band than drivers in the nonaugmented groups ($M = 2.95$ s). In other words, drivers in the off-target group made more rapid steering corrections than those in the on-target group, which is in line with a commonly observed finding in psychophysics called the onset advantage. As explained by Fisher and Miller (2008), research suggests that the sudden onset of a stimulus is a more powerful perceptual event than a stimulus offset, facilitating low-level perceptual processing and resulting in faster reaction times.

We also investigated the number of inside-to-outside bandwidth crossings. The on-target group performed equivalently to the nonaugmented groups throughout the experiment. The off-target group, on the other hand, started worst and gradually improved throughout practice and retention. Eventually, during delayed retention, the off-target group had considerably fewer bandwidth crossings than those in the on-target group ($M = 40.6$ vs. $M = 55.1$, $p < .001$, $d = −1.43$). This indicates that drivers in the off-target group had learned to avoid errors that were previously associated with vibration onsets.

Concluding, the difference in performance between on-target and off-target groups seems to be attributable to fundamental differences in the way humans process information when a signal switches from on to off or vice versa. Together with the earlier work on the same topic (Cauraugh et al., 1993; Gordon & Gottlieb, 1967; Williams & Briggs, 1962), it is now established that for effective learning of tracking skills, the onset of a stimulus should be associated with erroneous performance, not with correct performance. Our results also suggest that lane departure warning systems that become increasingly available in real vehicles may have a benefit for learning.

The off-target group had a higher steering reversal rate and steering entropy than did the nonaugmented groups. This lower level of steering smoothness was present during practice and extended to the retention sessions, indicating that it was something that was learned and that persisted. Less steering smoothness for the off-target group is in agreement with the finding discussed already, that the participants from the off-target group reacted more strongly to lane center errors. Indeed, a moderately lower level of steering smoothness could mean that the driver is controlling the car more actively. On the other hand, less smoothness may be indicative of inadequate anticipation of the curves ahead.

What constitutes optimal steering smoothness is clearly an interesting topic of further research. Using bandwidth feedback based on a predicted lane center error instead of the momentary lane center error may be a means to stimulate the learning of anticipatory steering behavior.

In this study, participants were trained to drive close to the center of the lane. It is acknowledged that driving around curves can be successfully accomplished in other ways than centering the vehicle in the lane. For example, approaching the inside of the lane may be considered a preferred driving style. We are planning to investigate the effectiveness of off-target feedback in our racing simulator with the bandwidth feedback centered on the ideal racing line. Furthermore, we hypothesize that the effectiveness of concurrent off-target bandwidth feedback is generalizable and can also be applied to the training of longitudinal control to keep the speed of the car within specified limits.

The present experiment featured 24 min of practice per participant and thus provided an indication of initial learning only. Asymptotic driving skill is normally obtained after months or even years of experience (Mayhew, Simpson, & Pak, 2003). It is therefore recommended to investigate the longer-term effects of augmented feedback. Another recommendation is to investigate the potential of augmented feedback using
more complex driving tasks, such as negotiating intersections.

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KEY POINTS

- This driving simulator study shows that off-target feedback is more effective for learning the lane-tracking task than is on-target feedback.
- Augmented feedback had strong beneficial effects during practice, but the benefit decreased gradually during the following retention sessions.
- Differences in training effectiveness were still detectable 1 day after the training day.
- Off-target feedback led to increased steering entropy and increased steering wheel reversal rate as compared with control-group performance.
- No noteworthy group differences were found regarding mean speed, secondary task performance, or self-reported measures.

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