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Evaluating the Effect of Reinforcement Haptics on Motor Learning and Cognitive Workload in Driver Training

Thomas G. Simpson^(✉) and Karen Rafferty^(✉)

Queen's University Belfast, Belfast, UK
{tsimpson07,k.rafferty}@qub.ac.uk

Abstract. Haptic technologies have the capacity to enhance motor learning, potentially improving the safety and quality of operating performance in a variety of applications, yet there is limited research evaluating implementation of these devices in driver training environments. A driving simulator and training scenario were developed to assess the quality of motor learning produced with wrist-attached vibrotactile haptic motors for additional reinforcement feedback. User studies were conducted with 36 participants split into 2 groups based on feedback modality. Throughout the simulation vehicle interactions with the course were recorded, enabling comparisons of pre and post-training performance between the groups to evaluate short-term retention of the steering motor skill. Statistically significant differences were found between the two groups for vehicle position safety violations ($U = 78.50$, $P = 0.008$) where the visual-haptic group improved significantly more than the visual group. The Raw NASA-TLX (RTLX) was completed by participants to examine the cognitive effect of the additional modality, where the visual-haptic group reported greater levels of workload ($U = 90.50$, $P = 0.039$). In conclusion, reinforcement vibrotactile haptics can enhance short-term retention of motor learning with a positive effect on the safety and quality of post-training behaviour, which is likely a result of increased demand and stimulation encouraging the adaptation of sensorimotor transformations.

Keywords: Haptics · Motor learning · Virtual environments · Driver training

1 Introduction

With the advent of AR and VR, virtual training systems are becoming effective educational tools in many applications, including surgery, industrial maintenance, flight simulators, and sports [1]. Haptics have the potential to advance the quality of virtual pedagogical systems with the additional sense of touch, enhancing the bandwidth of communication between the human and the computer with a supplementary channel providing access to haptic and tactile memory, typically ignored by conventional techniques. Advances in haptic technology

could optimise motor learning by encouraging the adaptation of sensorimotor transformations [2], potentially improving the safety and quality of training in certain driving scenarios; however, limited research has been conducted to assess the practical suitability of haptic implementations in these environments.

A rich corpus of psychology and neuroscience literature describes comprehensive observations of feedback effects on motor learning, yet real-world applications remain limited. Function-specific studies are responsible for maturing the literature further as the success of haptic feedback varies among application [3]. Implementations are typically in the form of haptic guidance, with the motivation to guide individuals to the correct technique in pursuit of reduced errors and improved training quality. Studies have demonstrated negative effects due to a reliance on the feedback and there are many instances where no statistical significance has been found between groups trained with haptic guidance and those without [4].

Poor results from studies regarding haptic guidance have led to the development of progressive haptic guidance, in which the amount of feedback is decreased over the training period, to gradually reduce learners reliance on the stimuli. This process has been applied to a steering task [4], with promising results achieved by integrating a haptic system for a wheelchair driving simulator with an algorithm incorporated to adapt the firmness of guidance relative to on-going error, which was administered through force-feedback in the wheel. Alternative implementations are also being investigated, such as error amplification which provides haptic feedback to increase movement errors during training. These are designed to improve learning practices and have been demonstrated as superior to haptic guidance in some scenarios [5]. This technique has also been applied to a steering task [6], where haptic feedback was delivered through the steering wheel in a virtual environment, commencing with guidance for initial training stages and progressing to error amplification. Insufficient tangible benefits of this approach suggest advancements are required to better exploit cognitive function during driving skill acquisition.

The motor learning literature expresses concern regarding the haptic guidance paradigm as it risks subject dependence on feedback, often compromising post-training performance [7]. Implementations providing error feedback could be beneficial as the motor learning impairment evident in haptic guidance is mitigated. This can be observed in a study [8] that generated seat vibrations when the vehicle travelled further than 0.5 m from the road-centre to promote lane-keeping in a driving simulator task, finding evidence that concurrent error feedback can improve short-term retention of motor behaviour. This study did not isolate modality, giving the haptics group and the control group different levels of information, such that any observed effect may not be due to haptic implementation.

Studies from the literature have not evaluated the potential of reinforcement learning using vibrotactile wrist-attached haptics, where most experiments have elected to use guidance feedback directly from the steering wheel, with varying reported results. The approach presented is a wrist-attached vibrotactile haptic

system to promote motor learning by generating increased motivation with concurrent reinforcement feedback during incorrect vehicle positioning. This technique could eliminate the motor learning impairment evident in haptic guidance, due to the feedback style reducing the risk of post-training reliance, as well as increasing the level of challenge by encouraging correct technique. Evaluations of cognitive workload associated with haptic techniques of this nature are critical for understanding how implementations modulate task demands and the effect that has on the motor learning process.

There is a clear research aperture for novel implementations of haptics in vehicle training scenarios; hence, the objective of the presented experiment was to evaluate the suitability of reinforcement vibrotactile haptics for a complex driver training scenario by observing the effect on short-term retention performance and cognitive workload. To accomplish this, 36 participants were divided into 2 groups where 1 group received visual-haptic training feedback and the other visual feedback. Exclusive haptic feedback was not studied as it presents inadequate information regarding impending instructions, limited to immediate reinforcement by concurrent implementation. This arrangement fairly isolated the variable of modality, with comparisons facilitated by simulation based metrics, to measure change in performance, and the RTLX questionnaire, to examine cognitive workload. The remainder of this paper includes descriptions of the system design and experiment procedure, as well as presentation and analysis of the results.

2 System Design

A performance driver training scenario was developed in Unity 3D, a game development engine designed for the production of interactive 3D virtual environments. A driving course was created utilising various components available on the Unity Asset store, such as models of track sections, trees, grass, barriers, and a vehicle; constructed to be demanding to help capture improvement, yet concise to sustain participant concentration levels. The vehicle physics were tuned to be realistic but also punishing for incorrect inputs, so that the error feedback offered significant benefit to the participant. The physical component of the system was comprised of a Playseat racing chair, a G920 wheel and pedals, and a NEC LCD 46 in. monitor with a resolution of 1920×1080 pixels, as seen in Fig. 1a.

An efficient path around the course was devised in conjunction with the Queen's University Racing Team, represented by a white 3-dimensional line visible in Fig. 1d, which participants were instructed to follow and learn. To explore the effect of modality, an Arduino based haptic system was developed to generate vibrations to the relevant sensory input if the projected trajectory was neglected, accomplished via USB serial connection to the Arduino at a communication rate of 9600 baud, with execution instructions transmitted from C# event scripting in Unity. An L298N motor driver board connected to an RS 423D DC PSU, powered two 3V RS PRO DC motors at 1.21 W, one for each wrist. A plastic inertial mass was screwed to the motor shaft to augment generated

Fig. 1. Simulator design

vibrations for distribution of haptic feedback. This was then implemented into a small plastic tube with epoxy fixing it firmly in place, creating a haptic module controllable from the computer. This was cable tied to a Velcro wrist strap for human attachment, covered with protective material for increased safety and comfort observed in Fig. 1a, remaining secured to the wrists of visual-haptic participants throughout the study.

Within Unity, a box collider system was created laterally along the vehicle to detect interaction with the instructed trajectory. This was accomplished with four box colliders spaced evenly apart, two inner and two outer colliders. When one of the outer colliders contacted the physical representation of the instruction, the haptics would begin to vibrate on the side that required movement, such that the right haptic motor would vibrate to indicate a right turn. This vibration would continue until the inner box collider contacted the projected path, detecting the participants return to an appropriate position.

3 Experiment

A controlled between-subjects experiment was conducted with 36 participants, with 18 in the visual and visual-haptic groups, where the independent variable being studied was the information type communicated to participants. Both groups were given identical visual instructions to fairly isolate modality.

The visual-haptics group received additional concurrent vibrotactile feedback designed to reinforce the motor learning procedure by promoting the correct steering responses, activated when participants failed to follow instruction. Subjects were required to negotiate the course with the objective of learning to follow the path communicated on screen that represented an optimised route. Each subject experienced the same location of visual instructions regardless of ability or performance, while frequency of haptic feedback was modulated proportionally to time spent in positional error.

3.1 Objectives

The experiment objective was to determine the quality of motor learning with concurrent vibrotactile feedback, through observations of improvements to safety and vehicle positioning, while observing cognitive workload for further analysis. Based on these objectives the following hypothesis was formed: the visual-haptic group would demonstrate improved motor learning because of the additional reinforcement, exhibiting greater cognitive workload due to more demanding stimulation.

3.2 Dependent Variables

There were three dependent variables in the experiment that were utilised to determine the suitability of vibrotactile haptics feedback in this context. The first dependent variable measured the frequency of participants off-road interactions; when the vehicle made physical contact with a component of the course that was not the road. For instance if the vehicle wheel made contact with the grass an error was counted, achieved with object colliders and collision detection in Unity. This dependent variable assesses the efficacy of the training from a safety perspective by quantifying vehicle positioning safety violations.

The second dependent variable measured the frequency with which the vehicle exceeded a distance of 4 m¹ from the instructed trajectory. This value was chosen arbitrarily prior to the experiment, based on the width of the driving course. An error was counted for every frame spent more than 4m from the suggested path, generating a metric for evaluating the short-term retention of motor learning by examining the post-training proximity to the suggested path.

The third dependent variable was the RTLX, a scientifically developed and validated psychological questionnaire that assesses cognitive workload. The raw version was preferred as studies are inconclusive over the benefits of the traditional version which consumes more time and participant effort [9]. This was conducted with 6 different criteria subjectively rated by each participant on a 21-gradation scale to yield a score from 0–100, subsequently averaged for a total score. Individual criteria were also assessed to evaluate any further differences. This variable is important to understand the human-behaviour elicited by the additional haptic modality, supporting interpretations and understanding of the effects observed in the simulation metrics.

¹ In simulation metres.

3.3 Participants

Participants were selected via department wide user study invitations. There were 36 participants, of which 2 were left handers and 34 were right handers. There were 16 males and 2 females in each group. The age of participants, in years, ranged from 19 to 63 where the visual-haptic group average age ($M = 27.37$, $SD = 9.97$) was similar to the visual group average age ($M = 25.79$, $SD = 11.62$).

3.4 Procedure

There were two types of different lap present in the study: a lap with instructions that the participants were required to follow, termed a training lap, and a lap without instructions where the participants were required to replicate what was learned in the training laps, termed a performance assessment lap. The training lap was defined by visual representations of the suggested trajectory for subjects to follow, as well as haptic feedback.

Initially the subjects drove two performance assessment laps, allowing evaluation of baseline performance for comparison with further laps. Subsequently, candidates would complete four training laps, then two performance assessment laps, then four training laps, and a final two performance assessment laps.

4 Results and Discussion

The objective of the presented results is to determine the effect of modality on motor behaviour improvements exhibited in the retention phase, relative to the pre-training phase, according to the dependent variables described. The first and second dependent variables were observed from data recorded to CSV files in the simulation, subsequently analysed in MATLAB and SPSS. Due to the non-parametric characteristics of the data the Mann-Whitney U test was required to compare the medians of the two groups, where all results presented use two-tailed exact significance values. Median and Median Absolute Deviation (MAD) values are displayed where necessary for a robust measure of variability. Results reporting improvement were calculated as percentage decreases by taking the error difference between the initial training phase and final retention phase, and dividing that by the initial training phase errors.

Statistically significant differences were found between the two groups ($U = 78.50$, $P = 0.008$) for the improvement between the initial performance assessment phase and the retention phase for the amount of safety errors generated by off-road interaction. The decrease of safety violations in the visual-haptic group ($M = 75.96\%$, $MAD = 31.66\%$) was greater than in the visual only group ($M = 43.75\%$, $MAD = 35.80\%$), displayed in Fig. 2b where the cross is the mean value. The results reveal an observable positive effect on participant motor learning for the visual-haptics group, encouraging appropriate vehicle positioning and path negotiation, which can be detected further in the amount

of errors generated by deviations greater than 4m from the projected trajectory, where statistically significant differences were also observed between the groups ($U = 99.00$, $P = 0.046$). The average error decrease in the haptic group ($M = 50.12\%$, $MAD = 15.67\%$) was significantly greater than in the visual group ($M = 41.48\%$, $MAD = 18.60\%$), reaffirming superior short-term motor skill retention in the visual-haptic group.

Fig. 2. Experiment results

In order to measure cognitive workload the RTLX was completed by the participants, which was scored and uploaded to MATLAB and SPSS for analysis. There were statistically significant differences between the two groups ($U = 90.50$, $P = 0.039$) where the haptic group ($M = 50.83$, $MAD = 12.02$) reported significantly increased cognitive workload ($+32.61\%$) over the visual group ($M = 38.33$,

MAD = 11.99). This result is expected due to improved performance, which can be explained by the increase in cognitive workload incited by reinforcement feedback.

Fig. 2a demonstrates the overall results of the RTLX, displaying the elements that were scored differently. Only two sub-elements had statistically significant differences, which were the scores for effort and frustration. For the effort exerted during the task, statistically significant differences were found between the two groups ($U = 91.50$, $P = 0.041$), with the haptics group ($M = 70.00$, $MAD = 1.60$) reporting a 16.67% increase over the visual group ($M = 60.00$, $MAD = 3.52$). A component of the difference in cognitive workload is hence due to effort. For the amount of frustration experienced in the task, statistically significant differences were found ($U = 82.00$, $P = 0.019$) with the haptic group ($M = 50.00$, $MAD = 5.63$) demonstrating a large increase (185.71%) in frustration over the visual group ($M = 15.00$, $MAD = 3.70$). This result further contributes to analysis of the overall task workload; the haptic group were frustrated significantly more than the visual group, indicative of the additional intensity of cognitive response elicited by the reinforcement learning.

Results suggest that the additional haptic modality has promoted motor learning with the effect of improving safety and path negotiation in the vehicle training scenario presented. Analysis of the RTLX reveals increased cognitive workload generated by the haptic modality, particularly frustration and effort levels, suggesting motor learning is supported by increasing the subjects exerted effort to accomplish the task by making it more demanding. Increased frustration levels are likely to be a natural concomitant of the extra stimulation to perform correctly, where error feedback is regular and energetic. These findings align with the hypothesis, with strong evidence to suggest that the improved motor learning is a result of reinforcement feedback influencing cognitive behaviour.

5 Conclusion

A virtual driving system was developed using the Unity game engine, designed to assess the effect of vibrotactile reinforcement haptics on motor learning and cognitive workload in vehicle training. Information regarding optimal vehicle positioning was delivered via visual-haptic and visual mediums, isolating modality for observation of improvements in safety and control. The frequency of off-road vehicle interaction was recorded, as well as the frame count accumulated while positioned greater than 4m from the immediate point on the suggested trajectory, allowing for objective comparisons of short-term motor skill retention. To further interpret the role of haptics in motor behaviour development, evaluations of cognitive workload were conducted with the RTLX. There was a significant difference in the short-term motor skill retention exhibited by the two groups. The visual-haptics group experienced greater decreases in safety and vehicle positioning errors, as well as higher levels of cognitive workload, particularly effort and frustration.

In conclusion, the additional haptic modality can improve short-term motor skill retention in driver training by increasing the cognitive workload of the

task. Analysis of the RTLX indicate this improvement is a result of more efforted responses from participants, likely from increased frustration experienced when committing positioning violations, which has encouraged the adaptation of sensorimotor transformations. Furthermore, the effect of the enhanced motor behaviour exhibited by the haptics trained group is an improvement in vehicle control, where participant negotiation of the course has advanced in safety and quality. It is hence established that vibrotactile reinforcement haptics are suitable for enhancing short-term retention of motor skills in driver training environments which could be adopted in a number of different training scenarios where steering control is involved such as piloting aircraft, emergency response driving, industrial machine operation, and conventional learner driving.

Future works should focus on developing more mature solutions, implementing aspects of artificial intelligence to the feedback based on informed psychological understanding of the motor learning process. Further applications should be researched to determine suitability for haptic feedback, as well as examining effects on long-term retention.

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