EXPLORING NOVEL AUDITORY DISPLAYS FOR SUPPORTING ACCELERATED SKILLS ACQUISITION AND ENHANCED PERFORMANCE IN MOTORSPORT

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ABSTRACT

This paper explores the design, development and evaluation of a novel real-time auditory display system for accelerated racing driver skills acquisition. The auditory feedback provides concurrent sensory augmentation and performance feedback using a novel target matching design. Real-time, dynamic, tonal audio feedback representing lateral G-force (a proxy for tire slip) is delivered to one ear whilst a target lateral G-force value representing the ‘limit’ of the car, to which the driver aims to drive, is panned to the driver’s other ear; tonal match across both ears signifies that the ‘limit’ has been reached. An evaluation approach was established to measure the efficacy of the audio feedback in terms of performance, workload and drivers’ assessment of self-efficacy. A preliminary human subject study was conducted in a driving simulator environment. Initial results are encouraging, indicating that there is potential for performance gain and driver confidence enhancement based on the audio feedback.

1. INTRODUCTION

For competitive sports people, performance feedback is critical to their sporting improvement [1,2]. Auditory feedback displays have proven successful in a range of sports, exercise and rehabilitation studies. For example, Schaffert *et al*. have successfully applied sonification to achieve rhythm improvement in elite and adaptive rowing [3,4] and, based on models of ideal performance, error sonifications have been shown to be beneficial for rowing technique, speed skating, and shooting accuracy improvement [5-9].

Frequency of feedback and issues of dependency are key factors in terms of the efficacy or success of any form of sports-related feedback: there is a general consensus that frequent feedback can degrade learning of simple skills but can also accelerate learning of complex skills [5, 9-11]. Surprisingly, therefore, since the early works of Hermann, Hunt, Stockman, and others [8, 11-13], there appears to have been an increasing loss of focus on highly complex skills learning in the sporting arena. Instead, much of the recent research in auditory sports feedback has focused on more simple or fine motor skill sports such as shooting [12], weight lifting [14], and running [15], with little attention being turned to tackling more complex or dynamic motor skills [5] which present a significant research and design challenge on account of the wide range of performance variables upon which to potentially provide feedback.

Auditory displays and mobile technologies are facilitating more frequent and effective feedback across a range of sports [16], and the complex, mentally demanding nature of motorsport presents a challenging and therefore interesting environment in which to explore the application of auditory feedback for performance enhancement. Unfortunately, despite the potential benefits of auditory feedback for complex sports-related skills performance enhancement, a range of factors in sports can present barriers to delivery and receipt of such feedback, and in few sports are these more prevalent than motorsport. Many racing cars do not have passenger seats to allow direct human observation and real-time feedback. Although verbal feedback (from engineer/coach to driver) *is* possible during racing sessions, it either incurs a time delay (e.g., post-session discussion) or is a proven (and therefore negative and so largely avoided) distraction to drivers when delivered over the communication system whilst driving. Racing cars are often heavily instrumented, thus capable of returning significant amounts of performance data yet there are often barriers to driver performance-based use of this data. The data systems often require manual download and computer access, limiting time available for analysis. Preparation for and attendance at events is expensive and time must often be spent optimizing mechanical aspects of a car, relegating the priority given to reviewing driver performance.

Our research aims to address the problems associated with effective delivery of performance enhancement feedback for complex skills acquisition in motorsport by designing and evaluating a real-time audio-based sensory augmentation and performance target matching interface based on cornering force (lateral G) values. We adopted a user-centred design (UCD) approach to address this challenge to ensure that driver and coach needs were closely observed and that the resulting feedback system would integrate within the drivers’ complex and dangerous domain. The remainder of this paper is structured as follows. Section 2 outlines the design process, including the results of knowledge elicitation activities, and introduces the auditory feedback system arising from these efforts. Section 3 describes our initial evaluation of the auditory feedback system, and Section 4 discusses the associated findings. Section 5 concludes this paper with discussion of future planned research.

2. DESIGN

As noted above, we adopted a user-centred design (UCD) approach to the design of our auditory feedback system in order to best capture driver and coach requirements and capabilities, and thus hopefully ensure the best chance of delivering an effective system to the motorsport arena. In essence, UCD places the user at the centre of all design activities and decision-making and we felt this was essential given the complexity of, and potential danger associated with, the motorsport domain. We directly observed coaching sessions between professional coaches and drivers at the iZone Driver Training Centre to establish a model of the coaching practice and methods currently in use. The same coaches also took part in knowledge elicitation interviews and design sessions during which potential data channels for feedback were shortlisted and discussed, and initial audio designs and mappings were explored.

In overview, the coaches' priorities broadly aligned with Barrass' golden principles for designing auditory displays [17]. They stressed the importance of (a) the appropriateness of the information and level of feedback provided and (b) a direct mapping between feedback and action. Coaches emphasized that any real-time audio feedback must not distract or annoy drivers (given associated risk of injury). Their remaining concerns aligned with Nees & Walker's vehicle-specific design principles [16] – namely, the detectability of changes in performance, discriminability from engine sounds, and identifiability of the required adjustment. The remainder of this section outlines the detail of what we learned by engaging with the coaches in pursuit of an optimal and useful audio feedback design, introduces the ultimate design, and very briefly discusses its implementation.

2.1. Racing Driver Training

The driver coaches we observed employ various techniques to support learning and to improve drivers' mental skills, performance and consistency. Professional racing driver training centres (such as iZone) and professional racing teams often utilize high-fidelity driving simulators for driver development to enable greater flexibility of training protocols whilst ensuring driver safety and minimizing costs when learning.

While reduction in lap times and number of mistakes are the prevalent measures of performance improvement, drivers and coaches additionally analyze performance on the basis of steering, brake, throttle and gear inputs, and subsequent G-force, speed, engine revolutions per minute (RPM), car attitude (oversteer/understeer) and time loss/gain traces. Analysis of a driver's performance on a given lap is typically overlaid with data from a reference lap of equal or greater performance, so that the driver may see where there is scope for further improvements.

Experienced and professional drivers often focus additionally on mental skills improvement, bringing more advanced psychophysiological measures such as gaze location (planning), breathing rate (exertion), heart rate, skin conductance (stress) into play when analyzing their performance. During coaching, experienced drivers are rarely instructed to focus on specific data channels; instead, they are guided to achieve goals such that the conscious mind is not stimulated as this can detract from desirable 'flow' state of performance (see later).

The professional coaches we worked with described the process of improving drivers' awareness of what they called the 'limit' – an abstract performance zone relating to the traction potential of the car's tires. While some drivers may not approach the limit (i.e., they are essentially under driving relative to the car's capacity), many drivers lose time by driving too far over the limit (or over driving). Over driving is typically characterized by frequent loss of traction and speed, while under driving is typically characterized by insufficient use of available traction, therefore requiring slower speeds. We discovered that a key difficulty in the coaching process is making a driver *aware* of the car's 'limit' and how to drive closer to it or reduce misuse of it. Coaches try to focus on sub-conscious interventions in an attempt to elicit the elusive 'flow' state, where faster sub-conscious control processes take over conscious actions and performance typically increases. During the learning process of a new track or car, drivers essentially search for the limit in the same way, albeit within the constraints of their personal level of performance.

2.2. Driver Environment

Motorsport is intrinsically a dangerous environment in which drivers' cognitive processing must happen fast for safe and effective performance. Motor racing is inherently *visually* demanding, especially given the speeds at which visual attention, perception, and processing must take place. Despite the visual demands of the environment through which the driver is moving at high speeds, vehicle cockpits often present drivers with a range of visual, high-frequency, performance indicators, including speed, RPM, best lap time, current lap time, predicted lap time, and lap time delta (best lap minus predicted lap) which the driver has to try to attend to in order to monitor his own (relative) performance. In addition, the typical *audio* environment of a vehicle cockpit is also 'busy', with associated implications for our audio design. Although the driver's audio sensory channel is arguably under less pressure than his visual or tactile sensory channels, the audio environment in which the driver is operating is loud and harsh; for example, a Formula Ford driver is exposed to an average 110dB during driving sessions [18]. The audio output from racing car engines is typically in the frequency range from 50 – 4000Hz, a similar range also being occupied by speech (300 – 3000Hz) [19]. Not only does this indicate why real-time speech-based feedback on performance can prove problematic, but it illustrates the complexity of introducing non-speech audio into the drivers' audio ecology.

Drivers already use their auditory channel to elicit cues as to their own performance: for example, engine frequency indicates the engine's RPM, wind noise provides a sensation of speed, drivers sometimes use tire screech as an indication of traction, and when competitively racing, drivers' awareness of other vehicles is built, in part, on their capacity to hear engine sounds from those other vehicles. This indicates that drivers are already accustomed to eliciting important cues/information via their sense of hearing which implies that feedback delivery via this sensory channel has potential for success but also that we need to be careful not to impede drivers' existing use of this input modality.

2.3. Audio Feedback Design

In consultation with professional coaches, we chose to focus our initial audio display design on skills acquisition by less experienced drivers. This was because, as already mentioned, optimization of use of data direct from the car's instrumentation (sensors) focuses on conscious processing as opposed to the more advanced, subconscious psychophysiological measures on which very advanced drivers focus for improvement. In essence, it was felt that there would be considerable merit to the concept of a continuous, target-matching sonification design associated with an established car's 'limit' but that this would require some conscious processing which would potentially disrupt the sub-conscious (flow) state of experienced, professional drivers. Furthermore, it was suggested that a greater return on investment would be possible for more novice drivers in that there would be more scope to achieve *accelerated* performance improvement in such drivers that would be much harder to achieve for experienced racing drivers.

Design sessions with coaches led to the conclusion that sonification of lateral G-force (indicative of tire slip) would be most useful in terms of helping less experienced drivers identify (find) and drive to, but not beyond, a car's established limit. In essence, our objective was to design a continuous, target-matching audio display whereby the current lateral G-force was displayed to the driver simultaneously to the established threshold ('limit') force for a given car and context, with the drivers' goal being to drive the car such that the audio for the former matches the latter. A cross-ear match between target and actual audio feedback would signify that the driver had reached and was optimally driving to the 'limit' of the car.

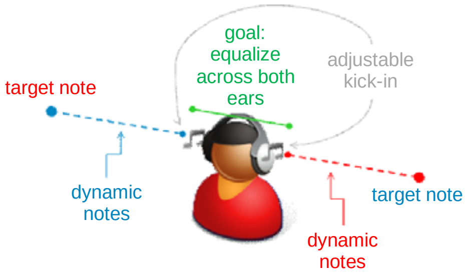

Figure 1: Model of target-matching sonification design.

During iterative refinement of the design concept, together with the professional coaches we chose to use a continuous sine tone for the audio feedback on account of the fact it was perceived as smoother and less distracting for the driver. Current lateral G-force values (starting at 0.2G) are sonified, via a sine tone oscillator, using a mapping algorithm from 400Hz up to 800Hz, and are synthesized along with the established performance target at fixed amplitude. Feedback volume was set to ensure clarity relative to ecological audio while avoiding distraction. A 'dead zone' up to 0.2G was included to avoid superfluous feedback on straights, since it is largely on cornering that lateral G-force is achieved and this is where drivers need support to identify the car's 'limit'. For a given car/context, a constant target feedback note is stereo-panned to the ear of the driver corresponding to the direction in which the driver is required to turn (e.g., the target audio is panned to the driver's left ear when executing a left turn), with actual lateral G-force feedback panned to the opposite ear (see Figure 1). The goal of drivers is then to increase the dynamically changing representation of the actual lateral G-force via the way in which they are driving the car until it matches the constant target tone: cross-ear tonal match indicates to the driver that the set 'limit' has been achieved. This close mapping of audio feedback to the required motor adjustment has been shown in other domains to be optimally usable and to support gaze and attentional focus [19] which is important in motor sport (i.e., via audio adjustment, we additionally want to encourage drivers to focus their visual attention on the corner into which they are driving). In this context, more sophisticated audio spatialization (e.g., distance from the ear to indicate target progression) was discarded because it was felt this would represent too much additional mental demand.

Our design achieves two goals: (1) sensory augmentation enhances drivers' awareness of the G-force being generated by the car relative to their driving style; and (2), performance targets inform drivers of their progression towards, and achievement of, benchmark targets. It is felt that the benefits of adopting our target-matching audio design include: (1) achieving an established target results in a rewarding aesthetic resonance, encouraging drivers to continue to achieve the target; (2) the cognitive distance from the drivers' physical movement to the audio is short, increasing usability and learnability; (3) non-achievement of target values is not overly negative – with statically set targets, drivers do not necessarily expect to achieve threshold G-force at all times and so we hope this reduces the psychological impact of error-only sonifications (which have the potential to distract, annoy, or reduce user confidence) whilst maintaining a key performance target and associated achievement perspective; and (4) external (coach) control of performance targets may reduce the risk associated with drivers attempting to achieve unrealistic targets.

2.4. Development

Although we are focusing initially on lateral G-force, our audio feedback system has been designed to support a *range* of vehicle sensor-derived data channels, allowing coach control over feedback. The system has been designed in Java with an extensible architecture which has supported rapid prototyping throughout the design process. Car performance metric data is read from either real-time or, based on an appropriate frequency, previously logged data files, and compared to the selected performance target, with audio output generated in accordance with the model described in the previous section. Targets can be set manually by a coach or can be extracted from a library of reference laps. In the case of the latter, a matching algorithm is used to find the nearest reference point to a driver's current location, and the target set accordingly. Output options include musical note mapping using MIDI or a sine tone generator. The JavaOSC package was used to send OSC messages to a PureData patch which allows run-time configuration of audio output. The driver simulation software used was rFactor (v.1.255C), chosen for its high fidelity and open architecture.

3. EVALUATION

We designed an initial evaluation protocol to allow us to conduct a first pass comparison of the efficacy of our audio display against standard performance review practice (as established during our observational studies – see Section 2.1). At its core, we established that our evaluation strategy would need to: allow drivers to become familiar with the audio feedback system; test drivers' rate of learning; test for any dependency effects; and obviously test for indicators of performance improvement as well as impact on drivers' subjective assessment of self-efficacy and workload. We introduced a competitive element (a prize for the best average lap time achieved) to incentivize drivers to maximise their performance as would be the case in normal race conditions.

For our initial study, we used a high-fidelity, fixed-base simulation pod, with 180° projection screens and high-fidelity force-feedback steering and pedals. The simulator was manufactured by Motion Simulators. Drivers were provided with Sennheiser HD202 II headphones via which we delivered the audio feedback (where applicable).

Eleven participants with an interest in and experience of motor racing (physical and/or virtual) were recruited from local universities and racing clubs. All eleven participants were male. To allow us to control as much as possible for external influences, we used a battery of questionnaires to investigate participants' previous driving experience, mood, and confidence levels. On arrival to the simulation centre, drivers were asked to complete a consent form, Motorsport Experience Questionnaire (MEQ), Motorsport Self-Efficacy Questionnaire (MSEQ), State-Sport Confidence Inventory (SSCI) [20], and Brunel Mood Scale [21]. The MSEQ was created according to Bandura's guidelines [22] and included separate ratings for the individual components of driving skill, including use of grip, braking, acceleration, cornering, consistency, smoothness, potential for improvement and experience of the track and car.

Session	Group A	Group C
Practice	Introduction to simulator and completion of 5 practice laps	
drivers fill out NASA TLX and MSEQ questionnaires		
Grouping	Driver briefed on audio feedback and the format & availability of post-session telemetry	Driver briefed on format & availability of post-session telemetry
1	10 laps with audio	10 laps without audio
drivers fill out NASA TLX and MSEQ questionnaires & given access to telemetry data to review		
2	10 laps with audio	10 laps without audio
drivers fill out NASA TLX and MSEQ questionnaires & given access to telemetry data to review		
3 (retention)	10 laps without audio	10 laps without audio
drivers fill out NASA TLX and MSEQ questionnaires		
4 (transfer)	10 laps of new circuit in same car with audio feedback	10 laps of new circuit in same car without audio feedback
drivers fill out NASA TLX, SSCI & MSEQ questionnaires & audio feedback questionnaire (Group A only)		

Table 1: Evaluation protocol.

A between-groups protocol was adopted (see Table 1), with each participant assigned to either the control group (C) or the audio feedback group (A). Group C drivers (5 in total) were provided access to post-session telemetry to guide personal performance (as per standard, existing coaching practice); in addition, Group A drivers (6 in total) also received the audio feedback as outlined in Section 2.3. All drivers were required to complete, in the same order, a practice session, three sessions (1-3) on rFactor's Northamptonshire National circuit, and 1 session on the Orchard Lake Road Circuit; both circuits were chosen for their simple, learnable layouts and long, medium-speed corners which would allow for meaningful performance target setting.

Drivers completed a 5-lap practice session; the results from this session were used to assign them to one of the two groups such that drivers' skill levels were balanced across the two groups as far as possible. At this point all drivers were briefed on the post-session telemetry they would be provided with and Group A drivers were additionally briefed on the audio feedback they would be receiving during the forthcoming sessions.

All driving sessions comprised 10 laps, after which drivers were asked to complete NASA TLX [23] and MSEQ questionnaires for the session and were given access to session telemetry to review in order to improve self-performance. Group A drivers were provided with 1.5G target audio and associated dynamic audio feedback for Sessions 1 and 2. In Session 3, this audio feedback was removed to test for dependency and retention (see Table 1). For Group A's final session, the audio feedback was re-introduced for a new track in order to evaluate drivers' learning approach and whether or not the audio feedback supports better skills transfer from one track to another. It took drivers around 90 minutes to complete the study.

4. RESULTS

A battery of measures were recorded during the study, and at time of writing, detailed analysis is still in progress. Here, we outline the results of preliminary analysis of the effects of the audio feedback on skills acquisition and driver performance, focusing on lap time (Section 4.1), lateral G-force (Section 4.2), and driver error (Section 4.5) since these are key coaching benchmarks for performance improvement. Additionally, we explore the questionnaire results in terms of the effect of the audio feedback on drivers' perceived self-efficacy (Section 4.4), workload (Section 4.5), and their opinions of the audio feedback (Section 4.6). Only descriptive statistics are used given the small number of participants and early stage of analysis and so no statistical significance is attributed to the findings reported below.

4.1. Average Lap Time

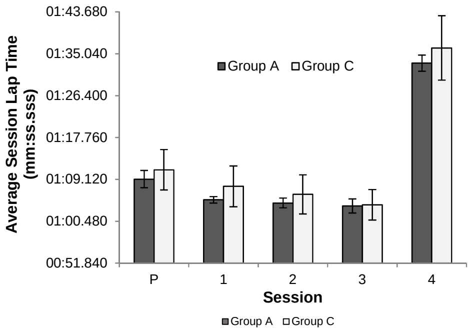

Figure 2: Average lap time by group and session (showing standard error).

Average lap time represents a measure of performance (and by association, consistency) under competitive conditions. Laps where vehicle speed dropped below 10km/h were classed as loss of control (LOC) events, and were removed from consideration here and analyzed separately. While minor driving error may skew average lap times, the latter remains a tried-and-tested measure of performance while avoiding effects of LOC. The average lap times by session and group shown in Figure 2 suggest that the audio feedback allows drivers to gain an initial performance advantage that takes drivers without such feedback more track time to achieve; over time, the results suggest that performance advantage would level out if feedback limits remain unadjusted, but since the goal of the audio feedback is to *accelerate* skills acquisition, these initial results show promise.

We considered the performance *gain* both as a group and by each participant from Practice to each of Sessions 1 – 3, all being laps on the same track (see Figure 3).

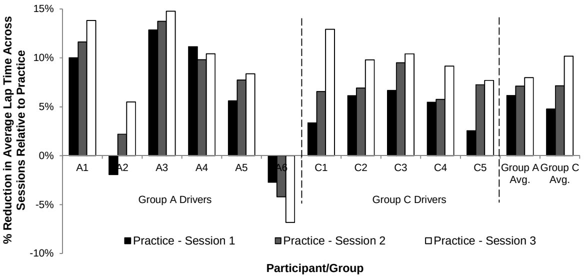

Figure 3: Average lap time improvement.

When we first consider the performance gain by group, we can see that Group A achieved a substantially higher performance gain from Practice to Session 1, with subsequent further gain in Sessions 2 and 3 starting to level off. In comparison, Group C drivers were slower to gain performance but ultimately surpassed Group A drivers in terms of overall gain by Session 3 (although it would seem that this was largely due to a spike in performance for driver C1 and it can clearly be seen that the drivers across Group A are more varied in skill level than those in Group C, despite best efforts to equalize skills across both groups). Given that Session 3 was designed to explore retention/dependency on the audio feedback for Group A, these results would suggest that either (a) a dependency effect is being witnessed for which the drivers suffered when the audio was withdrawn or (b) the threshold at which the audio feedback was set actually ended up falsely limiting the Group A drivers, who ended up driving in a constrained way to the learned 'limit' in comparison to Group C drivers who had no such 'enforced' limit. Looking at individual drivers, we can see that the most improved drivers overall are in Group A (drivers A1 and A3), *suggesting* that the audio feedback has the capacity to return substantial performance improvement. Furthermore, we can clearly see the Session 1 gain for the 3 most improved Group A drivers (A1, A3, A4) was in the region of 10%, 13% and 11%, respectively; the equivalently skilled/experienced Group C drivers (C2, C3, and C4, respectively) only achieved a performance improvement of 6%, 7%, and 6%, respectively. The performance of drivers A6 and A2 is worth specific comment, given they represent the least and most experienced drivers in the Group A, respectively. As can be seen, the audio feedback appeared to hinder rather than help A6's skills acquisition across all sessions; in this case, it would suggest that there may be a starting skills threshold below which drivers cannot effectively accommodate the additional level of feedback whilst learning. In the case of A2, the lack of performance gain is likely a result of the fact he was sufficiently experienced that the performance target (which was set to be consistent across all drivers) was too low and essentially constrained his natural driving capacity. This highlights the importance of personalized target setting such that drivers are given targets that push them to *their* attainable limits relative to the car's 'limits'. This is certainly something to consider in future evaluation studies which we hope to run with more professional drivers for whom starting skill levels will be more readily measurable.

4.2. Lateral G-Force

Analyzing the amount of time each driver spent within bands of lateral G-force can indicate where drivers are using more of the car's potential cornering performance. On average, drivers in Group A reduced their use of G-forces in the range of 0.75G-2.25G after Practice. From the data, it is not clear whether the audio feedback directed drivers towards using less G-force (on account of the target threshold) or whether such drivers took less time to execute their cornering on account of better use of the car's 'limits', thus reducing the time exposed to lateral G-force. Average minimum speed was less while maximum speeds were greater for Group A, which suggests that drivers provided with audio feedback gained lap time as a result of greater corner exit speed rather than higher cornering speed (embracing the motorsport mantra "*slow in, fast out*"). Further investigation will be necessary to explore the dependencies/causal effects here.

4.3. Driver Errors

We examined and categorized driver errors: as previously mentioned, major mistakes represent a total loss of control where vehicle speed dropped below 10km/h and laps where this occurred were removed from calculations of average lap times; minor mistakes represent a significant loss of speed compared to a driver's personal best, but in such instances the driver is able to recover control and continue racing. Focusing for now on the major errors, Group A drivers made more major errors in Practice (losing control in over half (56%) of the laps) but when supported by audio feedback in Session 1, the same group reduced their major errors by 30%. In contrast, Group C had a major error rate of 43% in both the Practice and first session. This suggests that the introduction of audio feedback between Practice and Session 1 played a substantial role in skills acquisition for Group A compared to Group C. Session 2 saw an unexpected rise in Group A's major error rate (an increase of 14%) whilst Group C saw a decrease in error rate of the same magnitude. Whilst the reduction in error for Group C is likely the consequence of continuing practice, the increased error rate for Group A is surprising; at the level of conjecture it may be that false confidence was achieved in Session 1 which encouraged drivers in this group to push themselves harder, with the consequence of more errors. Errors removed, the drivers in this group were still returning substantial lap time gains (see Section 4.1). When the audio feedback was removed for Group A, we see a further increase in error rate, whereas the control group's error rate remains largely constant. We have already discussed the potential for dependency and would propose to examine this more closely in future studies. Finally, and interestingly, when moved to a new track, drivers in Group A saw a substantial drop in error rates (to 28% which was on par with their optimal error rate performance in Session 1) whereas Group C saw a rise again in their error rate. For this final session, when baselined against their Practice session, Group A drivers were 30% more consistent than Group C drivers who were only 10% more consistent. This suggests that transferal of skill across tracks, when supported by the audio feedback, looks promising in terms of consistency of performance.

GPS traces were created of drivers' racing lines – an example of which is shown for turn 1 in Session 4 (Figure 4) – in order to illustratively visualize the location of errors and consistency of driving line. From these we can see that mistakes made by drivers in Group A seemed to cluster towards the outside of high speed corner exits due to their apparently greater confidence to carry speed into and through corners. In the example shown, both groups' errors were the result of excessive speed on the entry to the corner: while Group A drivers' response to such errors appears to be to adhere to the performance target and run towards the outside of the corner (finally losing control on the grassy run-off area), Group C drivers tended to respond via greater steering input, exceeding the performance limits of the car and losing control due to oversteer (resulting in spins towards to the inside of the corner).

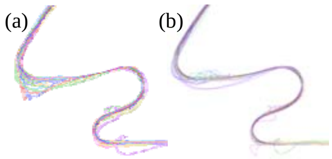

Figure 4: (a) Group A and (b) Group C GPS lap traces for turn 1, Session 4.

4.4. Driver Self-Efficacy

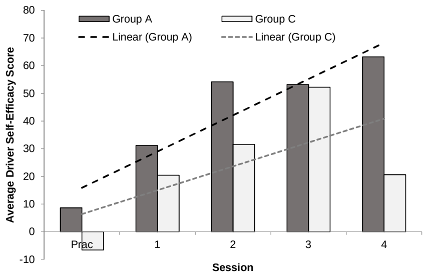

Figure 5: Average change in driver self-efficacy scores relative to pre-study levels.

Driver self-efficacy assessment (a proxy for self-confidence) was measured using the MSEQ questionnaire (see Section 3) after each driving session. Scores range from 0 to 360, with 360 representing maximum confidence in self-efficacy. Score deltas relative to pre-study confidence levels were calculated in order to analyze average change in confidence throughout the study (see Figure 5). Although Group A drivers did start with a higher baseline (Pre-Study) level of self-confidence (197) than Group C drivers (132), they returned consistently higher and more substantial increases in self-efficacy assessment from Pre-Study Practice to Session 1 (31.2) and Session 2 (54.2) than did Group C (20.4 and 31.6, respectively). On this basis, it would appear that the audio feedback was substantially improving drivers' sense of self-efficacy and therefore confidence. By Session 3, the scores for both groups had largely equalized; this represents a slight drop for Group A which lends further support to potential (albeit perhaps insignificant) dependency on the audio feedback once a driver is settled into the flow of a given track – their confidence dropping very slightly when it was removed. Most noticeably, however, when faced with a new track (Session 4), the drivers in Group A saw a further rise in subjective assessment of self-efficacy compared to a substantial drop for drivers in Group C; this lends strong support for the efficacy of the audio feedback in terms of increasing drivers' confidence when tackling an unfamiliar track. In the field of motorsport, psychological strength is a significant determinant of success, and so measurable increase in drivers' self-confidence is an important potential gain for the Group A drivers; in this case, it is accompanied by better average lap times in Session 4.

When considering the individual ratings for specific MSEQ scales, we noticed in particular that Group A's average self-efficacy score for '*My ability to maximize speed during a corner*' was more than double that of Group C in both Session 2 (representing a track with increasing familiarity) and Session 4 (representing a new, unfamiliar track). Group A's average scores were also consistently higher than Group C's for '*Using All Grip While Turning*' and '*Using All Grip While Accelerating*', both of which are core to tire slip and the facets of car performance 'limits' being studied. In contrast, the average ratings for Group A for consistency-related aspects (namely, driving line, turn-in points, and acceleration points) and knowledge of the circuit lagged behind those of Group C until Session 4 where we seemed to witness increased confidence on transferal to an unfamiliar track. Overall, the linear trend lines (see Figure 5) for Groups A and C would suggest that audio feedback is successful at accelerating and increasing drivers' subjective assessment of self-efficacy compared to standard performance evaluation.

4.5. Driver Workload

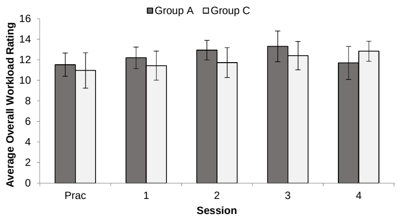

Figure 6: Average overall workload according to session and group (showing standard error).

The NASA TLX scale [23] was used to measure drivers' subjective assessment of the workload associated with each driving session. The overall workload scores by group and session are shown in Figure 6 and Figure 7 shows the breakdown according to workload dimension.

Perhaps unsurprisingly, the overall workload scores for Group A were slightly higher than those reported by Group C (see Figure 6) – that is, for all sessions other than Session 4, where the situation switched and Group A's average overall workload ratings dropped to their lowest since practice (largely influenced by comparatively low ratings for performance, effort and frustration) in contrast to Group C, which saw a further rise in their ratings, session upon session. This would, at least superficially, suggest that the audio feedback reduced the perception of workload when drivers were faced with a new track, having become accustomed to the training aid on another track beforehand. This would seem to tie in with the confidence ratings discussed previously, indicating that the feedback really starts to show its value over time in terms of skills transferal, leaving drivers better equipped to move between tracks with confidence.

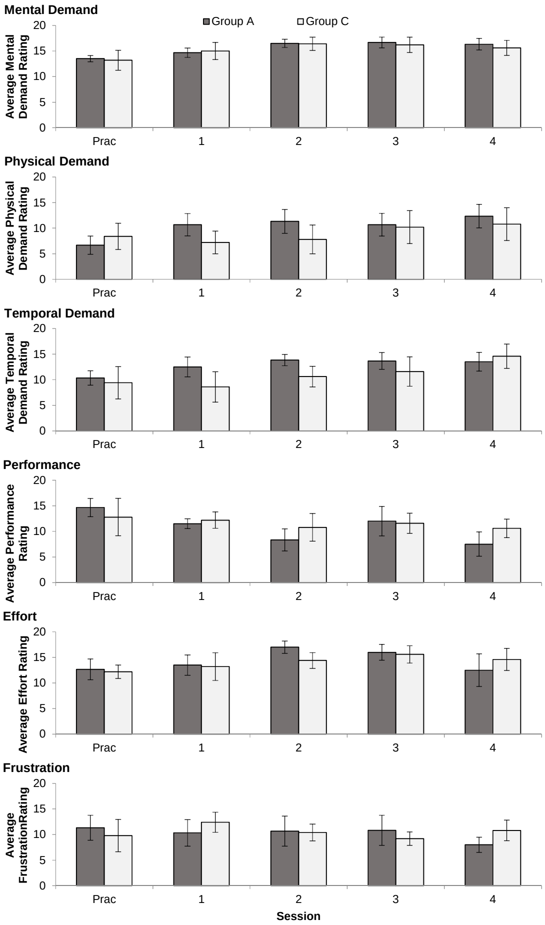

Figure 7: Average workload ratings per workload dimension according to session and group (showing standard error).

Surprisingly, given the additional feedback being processed by the drivers in Group A, they didn't report a substantive difference in mental demand compared to those in Group C (see Figure 7), suggesting that the audio feedback did not negatively impact drivers' cognitive load. There is evidence that the drivers in Group A found the sessions marginally more physically demanding. It is possible that, with audio feedback, drivers in Group A made more fine motor adjustments to their steering, with resultant fatigue likely explaining the greater physical effort ratings. As Group A drivers became more familiar with the track in Sessions 1 and 2, their temporal demand ratings showed more separation from their counterparts in Group C. At the same time, however, these drivers were more positive about their self-efficacy, so perhaps this is again reflecting heightened self-awareness. When provided with audio feedback, Group A drivers (after practice) appeared to be more satisfied with their own performance (tying in with self-efficacy again) and this only saw a reversal for Session 3 where confidence slipped when the audio feedback was removed. Interestingly, effort was largely consistent across both groups other than for Session 2 where Group A reported a higher level of effort (we are not entirely sure why there would be a spike here) and Session 4 where the effort was noticeably lower than for Group C at transition to an unfamiliar track. Finally, frustration was less for drivers in Group A when initially supported by the audio feedback; this evened out for Session 2 and inverted for Session 3 when the audio feedback was removed, returning to a level considerably lower than that of Group C at transition to the unfamiliar track on which Group A performed better.

4.6. Driver Feedback

When asked their opinion about the audio feedback, drivers' comments were mixed: in general, inexperienced drivers responded more favorably, while the more experienced drivers reported greater distraction. Based on all other findings, together with our first-hand observation of driver performance, we believe this is most likely due to the fact that the target performance level was set too low for the more experienced drivers, as discussed previously. Some drivers reported "choosing" when to listen but, on the whole, most drivers found the audio feedback easy to use and useful.

When asked to describe how they used the audio to influence their driving style, responses included "*I used the pitch to infer when I might get oversteer and loss* [of] *control/grip*", "*helps to negotiate corners on an unknown track"*, and "*gave me an idea of speed and how much speed I can carry through the corner*". These clearly indicate the audio was being perceived as conveying the information we had intended.

When asked how they felt the audio impacted their performance, several drivers indicated they felt it had improved their performance, with one driver interestingly noting that he felt the audio feedback had improved his performance, "*but only noticeable once audio was removed*". We asked drivers how (if at all) they might like to use the audio design in the future. Responses ranged from "*to learn a new track and explore limitations of corners*" to "*to help improve racing lap times*", with one driver suggesting an enhancement whereby audio was used to indicate when the rear of the car was losing traction. Overall, we are pleased with the positive response to the audio feedback, and encouraged that drivers interpreted its value as we had intended.

5. CONCLUSIONS

This paper has presented a real-time target matching auditory display, designed using user-centred design approaches, for the purpose of performance feedback for enhanced skills acquisition in racing drivers. A comprehensive testing approach was developed, and 11 novice drivers with a range of driving experience took part in a simulator-based comparative study to explore the efficacy of our system compared to status quo with no audio feedback. Based on our initial analysis we have shown auditory target matching and sensory augmentation to be effective during the learning and familiarization of new cars and tracks, especially in transferal of skills from familiar to unfamiliar tracks. The audio feedback has also shown great promise in terms of driver confidence enhancement. In the wider context, we have demonstrated that high-pressure, high-workload, safety critical, and sensory-demanding domains such as motorsport can benefit from auditory displays related to performance enhancement.

Whilst the results of our evaluation study are enlightening and encouraging, we recognize that there are limitations to our protocol. One such key limitation is the low performance target that was applied across all drivers, irrespective of skill level. This was done to avoid making erroneous judgments about skill levels and to avoid having to assume the role of coach for each driver, a role we were not equipped to fulfil. We had anticipated that the more experienced drivers would benefit in terms of confidence due to increased levels of positive feedback (i.e., they would achieve the target tone match more regularly). Although this does appear to have been the case, there is evidence that the low target performance level may have annoyed and constrained the more experienced drivers in Group A; with hindsight, we feel that had we deployed bespoke target levels per driver on the basis of skill (and skill improvement over the sessions), we would have seen more substantial improvement for the more experienced drivers as well as the less experienced drivers. This is encouraging for our future work, as we have implemented the capacity for such bespoke settings and are currently planning another series of evaluation studies which will incorporate coach control of individualized feedback.

In terms of future work, we plan to further analyze our data to look for more nuanced trends and correlations in driver performance. We plan to further evaluate alternative (vehicle-based) data channels for more experienced drivers. We are also currently planning, as already mentioned, a further evaluation study in which professional coaches will work with drivers, both with and without our audio feedback, to look for impact across carefully skills-matched pairs of professional drivers.

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