Preparing drivers for dangerous situations

A critical reflection on continuous shared control

J.C.F. de Winter, D. Dodou
Department of BioMechanical Engineering
Delft University of Technology
Delft, The Netherlands
j.c.f.dewinter@tudelft.nl

***Abstract*—Shared control (also known as continuous haptic guidance or haptically active controls) has recently been introduced in car driving. With shared control, the driver receives continuous force feedback on the gas pedal or steering wheel, so that human and machine conduct the driving task simultaneously. Experiments in driving simulators have shown that shared control reduces control variability and mental workload, and improves accuracy in path tracking and car following. Crucial to road safety, however, is not whether shared control improves performance in routine driving tasks, but what happens in dangerous situations when a conflict of authority occurs, or when the force feedback cannot be relied upon or is suddenly disengaged. Drawing on research into transfer of training, it is shown that shared control may induce aftereffects and may hamper retention of robust driving skills. Supplementary information should not be provided continuously, but on an as-needed basis, warning or assisting drivers only when deviations from acceptable tolerance limits arise.**

Keywords-shared control; guidance hypothesis; haptic guidance; concurrent continuous feedback; bandwidth feedback; road safety; transfer of learning; transfer of training

I. Introduction

In recent decades, a growing chorus of human-factors scientists have emphasized that humans and machines should not be seen as competing resources. Instead, the focus is placed on human-machine cooperation [1], joint performance [2], team play [3], [4], partnership [5], and complementarity [6]. Accordingly, shared control has been proposed as a means of making the best of cooperative human and machine resources, particularly in teleoperation [7]–[9] and car driving [10]–[16].

Integration of human and machine is intuitively appealing, but it changes the operator's task profoundly, and therefore requires critical assessment. This issue is particularly pertinent in car driving, an everyday task in which relatively minor control errors can pose a direct threat to road safety. The shared control philosophy is at variance with conventional advanced driver assistance systems that either automate the implementation of driving tasks (e.g., adaptive cruise control for autonomous distance keeping) or warn the driver only when safety margins are crossed (e.g., collision avoidance systems, blind spot monitors, lane departures warning systems).

In this invited paper, we discuss pitfalls of shared control and provide recommendations for effective augmentation of the driving task.

Most studies on shared control focus on hardware components and control schemes, while evaluation is concerned with the influence of shared control on momentary performance and control activity. The present study adopts a broader view by discussing what happens when the driving situation changes, and how the robustness of drivers' skills might be affected by shared control in the long term.

Note that this study is not a criticism of previous work on the topic. However, critical reflection might be beneficial for the shared control community and provide impetus for new research.

II. What is Shared Control?

Shared control is broadly defined as the situation where human and machine (nowadays often a computer) carry out a task simultaneously. Shared control is distinct from manual control (human does it all), full automation (machine does it all), and trading control (human and machine pass back and forth control alternately).

Sheridan and Verplank [17] distinguished between two forms of shared control: extension and relief. In the former, the machine carries out functions to help the human accomplish more than he could if he alone were in control. For example, many modern stealth aircraft are aerodynamically unstable and require computers to stay airborne and assist the human during flight maneuvers. A good example in car driving is Electronic Stability Control (ESC), a system that can brake wheels individually, which the human driver cannot do.

Relief means that the machine takes part in information-processing and control activities to reduce the task demands on the human. An example is a system that detects the distance to the preceding car and supplies force feedback on the gas pedal to help the driver maintain a safe and comfortable distance.

Further types of shared control have been proposed in the context of decision support and other forms of mental activity [18]; these are not treated in this paper.

In line with the topic of this special session, this paper is concerned with relief shared control that deals with force feedback on the control interface. Specifically, shared control is defined in this paper as the combination of the following properties:

- *Haptic*. The machine provides active force feedback other than the task-intrinsic self-aligning steering torque. Other conceivable forms of shared control (e.g., brain-computer interfaces [19]) are beyond the scope of this paper.

- *Simultaneously sharing the same control interface*. Force feedback is provided at the same time the human is carrying out the task and on the same control device that the human is using to carry out the task.
- *Continuous*. Overridable, continuous feedback is provided during normal (i.e., routine) task operation. This definition excludes feedback applied as a warning or violation signal (e.g., lane departure warning, lane departure assistance, speed limiter) or feedback applied during special maneuvers only (e.g., obstacle avoidance).
- *Controlled system remains unaffected*. The system dynamics in terms of the relationship between control interface position and vehicle state do not change.

Shared control systems fulfilling these criteria include gas pedal feedback during car following [20]–[22] and steering wheel feedback during path tracking [12], [14]–[16], [23]–[26]. Shared control has also been called (continuous) haptic guidance [24], [25] and haptically active controls [16].

III. WHY SHARED CONTROL?

Shared control satisfies several principles of good display design, in particular *redundancy gain, minimizing information access costs*, and the *principle of multiple resources* [27]. With shared control the driver has haptic access to perceptual variables, such as the approach speed of an oncoming vehicle, for which the visual system is known to be inaccurate [28], [29]. Car driving is predominantly a visual task [30] and visual inattention is a frequent cause of accidents [31]. Redundant haptic cues are a promising means to reduce information loss and keep the driver informed about the impending situation. Shared control also facilitates the use of rapid reflexive processing. Ideally, the driver can comfortably rely on the applied feedback forces and conduct a so-called force task [10].

Consequently, shared control is expected to yield performance improvements during routine driving tasks. The following advantages of shared control in comparison to manual control have been empirically demonstrated in driving simulator studies: more accurate path tracking [12], [14], [15], [23]–[25], reduced distance variability during car following [32], [33], reduced control activity [33], and reduced workload as demonstrated by faster reaction times and better secondary task performance [12], [16], [21], [22], [32], [34]. These effects are self-evident in some steering systems: When the driver conforms to the guiding forces (or even releases the hands from the steering wheel), the machine will stay in control and accurately steer the car along the target path (e.g., [35]).

Some negative results of shared control have been demonstrated as well, including, most notably, an increased number of collisions because the shared control did not guide the driver around objects in the middle of the path [12]. Furthermore, usability issues have been documented, such as increased physical effort because "drivers were not agreeing with the haptic guidance" [24] [25], oscillations induced by the guidance forces [15], and reduced comfort due to the system's inaccurate representation of driver's perception of risk [22].

IV. RISK FACTORS OF SHARED CONTROL

Metaphors are often used to explain the working mechanisms of shared control. Shared control has been compared to having a copilot [12], and with the close communicative relationship between rider and horse [36].

It may be useful, however, to step away from these metaphors, particularly because they involve the interaction of two living organisms, and describe what actually happens during shared control. With shared control, a machine acquires environmental variables using sensors, translates them into a perceptually meaningful metric, and implements this metric in the form of a feedback force on the steering wheel or gas pedal. We recognize the following risks in this "copiloting":

Disengagement of shared control. Components of shared control hardware may contain design flaws and/or may fail. It is also possible that the machine provides inaccurate feedback in certain circumstances. For example, in curve negotiation, the in-vehicle sensors may misestimate the radius of a curve, resulting in inappropriate steering wheel torques. Furthermore, there are always situations for which the shared control is not designed to operate, such as city driving and emergency maneuvers (cf., the cruise control system that does not apply the brakes).

Special algorithms have been proposed to allow the machine to cope with complex traffic situations. De Winter et al. [22] developed a weighting scheme to represent multiple vehicles driving in front of the host vehicle, including highway situations where vehicles cut in between the host vehicle and lead vehicle. Tsoi et al. [25] presented a haptic guidance system for lane changing, a task *opposite* to lane keeping. Despite these efforts, there will inevitably be situations where the human has to reclaim full manual control, a point at which the driving task suddenly changes from a combined visual-haptic task into a visual-only task; see next section for potential consequences.

Who has authority? Shared guidance presents the traffic situation via a one-dimensional channel (a feedback force on either the gas pedal or the steering wheel). There may be situations where simplifying the environment into one metric provides ambiguous information to the human.

When driving with full automation of the driving task, such as with automatic lane keeping, it is clear that the machine is in control and that the human supervises automation. With shared control, however, the level of guidance varies continuously depending on the amount of physical feedback force. It may be at any level from almost manual control to almost full automation (i.e., high level of haptic guidance but still keeping the human in the loop), leading potentially to confusion and/or conflict over who is in charge of the driving task and what the driver must do: "obey" the machine, or counteract the force?

Automation is well known to reduce workload, but ironically, it may make an already difficult task even harder [37], [38]. This effect may be aggravated in shared control.

Think of encountering an obstacle in the middle of the road, a situation demanding an evasive maneuver, yet shared control keeps the car centered in the lane. In this situation, the driver cannot perform a force task anymore but should counteract the force, leading potentially to increased workload and delayed response as compared to unassisted driving or full automation (not to mention the risk of a crash).

"Arbitration" or "negotiation" have been suggested as a means to resolve conflicts when multiple solutions are possible (e.g., evade an obstacle by steering either left or right) [39]. However, arbitration is mostly based on dialogue rules and psychological conflict solving [39], methods that are more suitable for human-human or human-animal communication rather than human-machine communication.

Overreliance and complacency. Complacency is defined as inadequate monitoring and information seeking, or "self-satisfaction which may result in impaired vigilance based on an unjustified assumption of satisfactory system state" [40]. A study investigating the consequences of automation on supervisory control found that complacency (also called automation bias) was independent from the level of automation and that even "medium levels of automation, which have been recommended to reduce 'out-of-the-loop-unfamiliarity' problems in human-automation interaction (e.g. Endsley & Kiris, 1995), do not represent an efficient countermeasure for this issue" [41]. Complacency and overreliance have been regularly reported as the cause of accidents. We hypothesize that overreliance will be more of a problem with shared control than with full automation. When driving with full automation clearly the driver's task is to monitor whether the computer adequately controls the task. However, with shared control, as neuromuscular analyses have already shown [10], the driver is intrinsically stimulated to respond to the machine's suggestions by comfortably giving way to feedback forces.

Skill loss. Skill loss, also known as deskilling or skill degradation, is a serious concern in the highly automated aviation industries [42]–[46], but it could also play a role in shared control. When driving for prolonged periods of time with a shared control system, it is possible that the driver will gradually lose the skill to drive based on all-visual cues.

V. Shared Control and the Guidance Hypothesis

The previous section stressed that it is important to consider what happens when the shared control is disengaged, or when a conflict of authority occurs or the force feedback cannot be relied upon. Little empirical research is available on this topic in the domain of shared control in car driving. However, transfer of training research—that is, the study of how performance depends on prior experience—reveals some striking findings about the effects of haptic guidance on the retention of motor skills.

Research into how the central nervous system learns to control movements indicates that when humans are repeatedly subjected to forces, adaptive aftereffects occur when the forces are suddenly removed [47]. The aftereffects are mirror images of the effects observed when the humans were initially exposed to the forces [47], [48], see Figure 1. It does not take a vivid imagination to realize the potential consequences for a driver making an erroneous steering input the moment when the shared control system was just turned off or on.

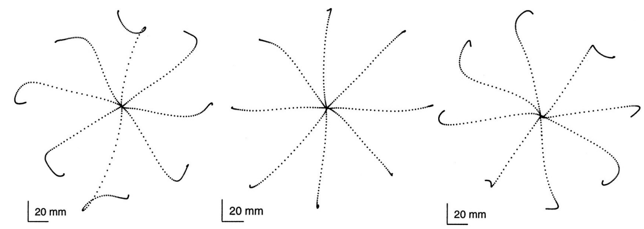

Figure 1. Effects of force field on hand paths. The human was conducting center-out reaching movements in a two-dimensional plane, while a robotic device was generating a force field pushing the hand to a direction perpendicular to the target. A typical hand path of an untrained subject in a force field is shown at the left. With repeated exposure to the force field, the human became able to move straight towards the line (middle). When the force field was unexpectedly switched off, aftereffects occurred, with hand trajectories that were approximately mirror images of those observed when the subjects were initially exposed to the force field (right), indicating that the nervous system had developed an internal model of the applied forces. Reproduced from Figure 2 of "Functional stages in the formation of human long-term motor memory," by R. Shadmehr and T. Brashers-Krug, 1997, *J. Neurosci.*, vol. 17, p. 412. Copyright 1997 by The Journal of Neuroscience [47]. Reprinted with permission.

Long-term effects have been observed as well. The guidance hypothesis, formalized by Salmoni et al. [49], states that augmented feedback (the definition of which includes not only haptic guidance, but also other types of supplementary information, such as knowledge-of-results feedback and concurrent visual feedback) facilitates performance when provided, but leads to deteriorated performance after feedback is withdrawn [50]. In fact, the guidance hypothesis predicts that "feedback that is relatively more guiding would be expected to have greater detrimental effects on motor learning" [51].

Guidance tends to make people rely upon the supplementary information and distracts them from learning to pick up the task-intrinsic visual feedback from the environment. Guidance can also lead to overcorrective behavior that occurs when the human responds to trivial errors [52], [53].

Several studies have demonstrated the guidance hypothesis for shared control and other forms of haptic guidance [54]–[58]. A classical example of the guidance hypothesis for haptic guidance (in this case non-overridable physical feedback) is illustrated in Figure 2. In this experiment, subjects had to move their arm towards a target using a visually occluded angular positioning lever. For the high-guidance group, a physical block indicated the position of the target in 83% of the trials in each of six practice sessions, whereas for the low guidance group the physical block appeared in a fading schedule (in 50%, 33%, and 16% of the trials in the first two, next two, and final two practice sessions, respectively). Guidance feedback evidently improved motor performance when it was provided (i.e., during practice), resulting in perfect accuracy on those trials. Strikingly, after guidance was removed (i.e., during retention), accuracy of performance deteriorated, particularly in the high-guidance group. The relative differences were particularly large after one night of sleep (delayed retention) and when transferring to a new target position, indicating that these effects were persistent [51].

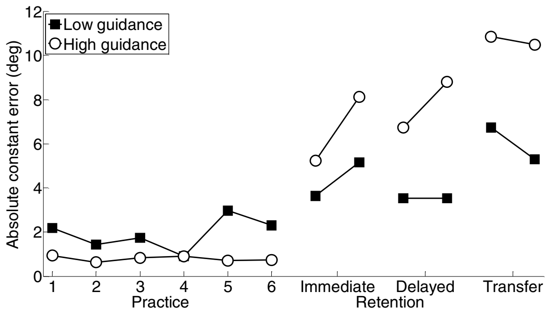

Figure 2. Group means of six-trial sessions of the absolute constant error scores for practice, immediate retention, delayed retention (after one night of sleep), and transfer to a new task for high and low guidance. Subjects had to move their arm towards a target using a visually occluded angular positioning lever. High guidance: during the six practice sessions, subjects moved to a physical block placed at the target position on 83% of the trials and moved to the subject-recalled target position without the block for the remainder of the trials. Low guidance: during the six practice sessions, subjects moved to the block at the target in a fading schedule. Specifically, guidance feedback was provided on 50%, 33%, and 16% of the trials in the first two, next two, and last two practice sessions, respectively. In retention, guidance was removed for both groups. Adapted from Figure 3 of "Effects of physical guidance and knowledge of results on motor learning: Support for the guidance hypothesis," by C. J. Winstein, P. S. Pohl, and R. Lewthwaite, 1994, *Res. Q. Exerc. Sport*, vol. 65, p. 319. Copyright 1994 by Research Quarterly for Exercise and Sport [51]. Adapted with permission.

VI. How to Support the Driver

How should a system support drivers without making them dependent on supplementary information, and allowing them to respond effectively when the force feedback can no longer be relied upon?

Research in motor learning suggests that augmented feedback should be provided sparingly [59]. In line with this observation, Crespo et al. [60] found that in learning to steer a simulated vehicle, haptic "guidance-as-needed" was more effective than "fixed guidance". Augmented feedback may benefit learning complex motor tasks (timing, balancing, complex sports movements) [61]–[63] and may assist beginners to prevent mental overload [61]. However, supporting drivers who already carry out their tasks efficiently would not bring benefit, or may even distract them from extracting the relevant visual cues from the environment.

In this respect, motor-learning researchers have found a solution in off-target bandwidth feedback (also called dead zones) [64]–[68], which switches on only when the human makes a large error. Advantages of off-target bandwidth feedback are that it directs attention in critical circumstances to prevent large tracking errors, whereas it does not intervene when the human performs within acceptable tolerance limits. The working principle of off-target feedback is in line with traditional warning systems in car driving [69]–[72], and with the notion that car driving is a satisficing task, not an optimizing task [70].

Figure 3 illustrates the beneficial effect of haptic bandwidth feedback in a lane keeping task in a driving simulator [73]. Subjects without a driver' license had to keep their car in the center of the right lane of a rural road. Off-target feedback was a seat vibration that switched on only when the learner was driving more than 0.5 m away from the lane center. Conversely, in on-target feedback, vibrations were activated when driving nearer than 0.5 m from the lane center. The results showed that off-target feedback was superior *both* when provided (i.e., during practice) and when removed (i.e., during retention), as compared to on-target feedback.

These experimental results suggest that off-target feedback provides useful information for learner drivers, while not distracting them from picking up task-relevant visual cues from the environment. Other advantages of off-target feedback are that drivers respond intuitively to a signal that switches on (as opposed to one that turns off), and that the amount of feedback they receive is automatically reduced as their performance improves [73].

Note that the example of off-target bandwidth feedback provided in Figure 3, where drivers were supported using seat vibration, is not an example of shared control as defined above (it is not continuous and it is not sharing the same control interface). The results serve to illustrate the advantage of off-target bandwidth feedback.

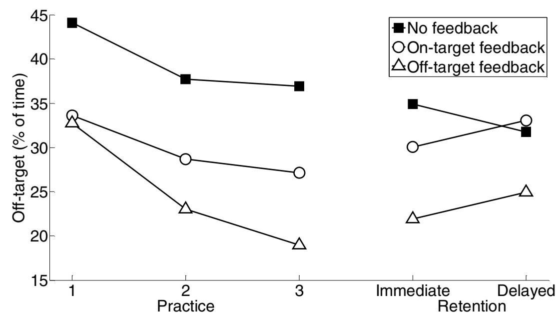

Figure 3. Group means of the percentage of time that the center of the subjects' car was outside a 1-m wide band around the lane center during 8-min driving sessions for practice, immediate retention, and delayed retention in a driving simulator. Subjects without a driver' license had to keep the car in the center of the right lane. No feedback: no augmented feedback. On-target: seat vibrations when driving within the 1-m-wide band during practice. Off-target: seat vibrations when driving outside the 1-m-wide band during practice. In retention, feedback was not provided to either of the groups. Adapted from Figure 2 of "The effect of concurrent bandwidth feedback on learning the lane keeping task in a driving simulator," by S. de Groot, J. C. F. de Winter, J. M. López-García, M. Mulder, and P. A. Wieringa, 2011, *Human Factors*, vol. 53, p. 59. Copyright 2011 by Human Factors [73].

VII. Discussion

Shared control provides benefits compared to manual control as long as the system operates in the situation it is designed to operate in (e.g., continuous path tracking and car following). However, if the goal is really to reduce workload and control effort, and to maximize accuracy of performance during routine driving tasks, then higher levels of automation, such as ACC and automatic lane keeping, fulfill these criteria far better [16].

Shared control has its pitfalls. In dangerous situations, confusion may arise over who has authority, the human or the machine. Furthermore, shared control might induce complacency and increase workload if the driver is confronted with a situation in which force feedback cannot be relied upon. Drawing on research into transfer of training of basic motor tasks, this paper showed that haptic information benefits the motor task when it is provided. When the supplementary information is withdrawn, however, latent problems become apparent, namely aftereffects and reduced ability to carry out the task effectively based on task-intrinsic cues.

In conclusion, there is good reason to believe that for the sake of road safety drivers should *not* be assisted in a shared-control manner, that is, in routine situations when they already perform at a reasonable standard (i.e., in the far greatest part of the driving task). If supplementary feedback is provided, it should be done on an as-needed basis, warning or assisting only when the driver deviates from acceptable tolerance limits. A number of such haptic feedback systems already exist. Examples are systems such as a counterforce on the gas pedal when a speed limit is exceeded (sometimes combined with other warning systems or restricted fuel injection [74]–[78]), and systems that prime or guide the driver in case of impeding collisions, blind spot intrusions, and lane departure [14], [79]–[83] (for an overview of such commercialized systems, see [84]).

One may also consider other forms of assistance that extend the performance envelope. An example is Electronic Stability Control, a system regarded by many experts as the most important advance in motor vehicle safety. This system does not intervene during normal driving but enables actions that the unaided human is unable to accomplish. Judging from past experience in aviation and train driving (e.g., Automatic Train Protection, Anti Collision Device), in case of serious impeding collisions, automation may be preferred to take over completely, without any possibility for human override [85].

Future research in shared control should not just be directed at how the driver, as a closed-loop controller, optimizes around a certain target value. Instead, transfer studies that evaluate the robustness of skills and the ability to cope with new situations are recommended. Future research could also investigate the effect of shared control on cognitive engineering constructs such as complacency, workload, and situation awareness.

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