T9+HUD: Physical Keypad and HUD can Improve Driving Performance while Typing and Driving

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ABSTRACT
This paper introduces T9+HUD, a text entry method designed to decrease visual distraction while driving and typing. T9+HUD combines a physical 3x4 keypad on the steering wheel with a head-up-display (HUD) for projecting output on the windshield. Previous work suggests that this may be visually less demanding way to type while driving than the popular case where both the touch screen keyboard and the display require shifts of visual attention away from the road. In particular, T9 should allow experienced typists push keys without looking at the keypad, and the HUD allows the driver to keep focal vision closer to the road environment. We present a prototype design and report first results from a controlled evaluation in a driving simulator. While driving, the T9+HUD text entry rate was equal compared to a dashboard-mounted touchscreen device, but it reduced lane deviations by 70%. In addition, there was no significant difference between T9+HUD and the baseline driving in lane-keeping performance. T9+HUD decreased glance time off road by 64% in comparison to the touchscreen QWERTY. We conclude that the data are favorable and warrant more research on attention-reducing text input methods for driving.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

Author Keywords
Text input; Automotive User Interfaces; Car Interfaces; T9 text input

INTRODUCTION
This paper contributes to research on user interfaces aiming to reduce driving accidents caused by distraction. In the US alone, despite being illegal in many states, nearly 341,000 traffic injuries occur annually where texting is involved [23]. In addition to personal devices, entering text with in-car systems is becoming more prevalent with navigation systems and integrated systems for media and communications.

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Sales of vehicles with touch screen interfaces is estimated to increase to more than 61 million units in 2021 [13]. These systems are often operated via touch-screens that offer poor tactile feedback and demand visual attention [16, 34], thus contributing to driver distraction. We believe it is important to study approaches that may be better acceptable by drivers and thereby more successful than restrictions and legislative measures. Statistics suggest that drivers continue using their smart phones for texting while driving despite of bans [5]. While self-driving cars might solve this problem in the long term, texting while driving is an acute and increasing problem with fatal consequences.

This paper studies an alternative design of a text entry method for in-car typing. Designing a text entry method, in general, requires multiple decisions on the positioning and design of keys, display, and error correction, among others. While a vast amount of research has been carried out on in-car typing, no text entry method has been identified that would strike an acceptable balance between distraction and text entry performance. Previous research has examined suitable locations for keys [15], including the possibility of using the steering wheel [7, 22]. Other studies have tested virtual keyboards placed in

Figure 1. T9+HUD combines a physical 3x4 keypad on the steering wheel with a head-up-display (HUD) for projecting output on the windshield.

the center stack [38]. However, it is not known if such designs can help significantly in reducing driver distraction.

This paper presents results from an attempt to revise the design of a text entry method for driving. The principal goal of the proposed design is to encourage drivers not to shift gaze from the road to the typing device as much, and to encourage maintaining their hands on the wheel, even while typing. *T9+HUD*, shown in Figure 1, combines a physical 3x4 keypad on the steering wheel with a head-up-display (HUD) for projecting output on the windshield. T9 is a highly efficient reduced keyboard allowing high text entry speed on full sized keys. Even if the T9 technique, when used on a hand-held cellphone, has been shown to bear a negative impact on simulated driving performance [4], we hypothesized this setup may be less visually distracting when combined with text output on HUD. In particular, the T9 keypad should allow typists, who are experienced with the technology, push keys without looking at the keypad [25]. On the other hand, the HUD allows drivers to keep focal vision closer to the road environment. This should better allow experienced drivers to utilize peripheral vision for lane-keeping and hazard detection than while operating with center console displays [31]. Moreover, like with previous designs, because hands could be kept on the wheel, steering performance could be improved compared to one-hand steering. These properties should allow drivers maintain their gaze more on the road and improve their lane-keeping performance.

In the remaining sections of the paper, we report previous work. While both T9 and HUD have been studied in the past, this is the first paper combining the two in this particular setup. We then present a prototype design for T9+HUD. T9+HUD can be implemented in many ways. Our implementation uses a physical key-grid with large buttons and a HUD projected to a display by using a light source and a special film on the windshield. The design was validated in a controlled experiment in a simulated driving environment using eye tracking and standard lane-keeping metrics. We compared performance to one state of the art in-car text entry design: a dashboard-mounted touchscreen keyboard. This design is becoming more prevalent in modern cars. The results are favorable, showing that while not distraction-free, T9+HUD was associated with a significant drop in dependent measures of distraction.

PREVIOUS WORK ON IN-CAR TEXT ENTRY

The commercial market is presently experimenting with various ideas for in-car text entry. iDrive provides drivers with a push and turn navigation mechanism. Mercedes Benz and Audi have their COMAND and MMI controllers, respectively. However, these force drivers to remove their hands from the wheel to reach the central stack. The decoupling of the display is a common drawback, which forces drivers to shift eyes away from the road. More popular alternatives, built-in touch displays located in the vertical center stack represent another type of interaction devices that face issues such as the lack of haptic feedback, making their utilization more demanding for visual attention.

HCI research has looked at alternative modalities and physical designs to improve text entry in cars. Handwriting has been proposed as an alternative modality [15]. When the input device was planned on the steering wheel, it was well-received by users. Some research has looked at thumb-based techniques [7], by using a small touch-pad called Synaptics StampPad embedded in a computer game steering wheel and the EdgeWrite gestural text entry method [39]. EdgeWrite was found to be faster than selection-based text entry by about 20 to 50 percent. However, the level of distraction was considered to be too high for being an option for typing while driving.

Research has compared different keyboard layouts in the center console of a simulator [38]. The keyboard used a QWERTY layout, an ABC layout, or a novel technique composed of 5 buttons. The 5-button technique got higher workload ratings than the other techniques, but there were no differences in driving performance. The back of the steering wheel has also been considered. Researchers have proposed installing sliding sensors and physical buttons at each side of the steering wheel [22]. A transparent display was used to present information that can be fixated while still allowing peripheral vision for lane-keeping and hazard perception. Moreover, voice-to-text solutions have also been studied. In particular, these could be visually low demanding, but currently these are inefficient, unreliable and typically require also visual attention for checking the spelling of the message [21].

Besides input, designing a text entry system requires considering the design of the text display. The current understanding is that HUDs are preferable to in-built "head-down displays" (HDDs). Studies comparing HUD and HDD [1, 18] have concluded that HUD allows drivers to react faster to an abrupt event. In addition, it seems to support more consistent speed control and causes less mental stress [19]. Nonetheless, another study suggest that the use of HUD could result in attention capture and increased reaction times to sudden events when compared to baseline performance [27]. Also, the HUD benefits do not hold under the high workload of unexpected events, during which HUD users experience detriment to both the driving task and roadway event response [12, 6].

T9 is a highly efficient reduced keyboard allowing mediocre text entry rates on full sized keys [3]. A study reports results of 10.98 words per minute(WPM) to 25.68 WPM while using this method [14]. T9 contains 12 keys, organized in a grid of 3 by 4. What distinguishes T9 is that multiple letters and symbols are assigned to each key, generating ambiguity in the textual keystrokes. To type a word the user presses a sequence of keys, which generates a succession of letters. This succession of letters is analyzed with a complete dictionary that contains spelling words that are expected the user to enter reasonably. The words that match the sequence of keystrokes are shown to the user. These words are presented in decreasing order according to their frequency. If the predicted word is not the desired one, the user can continue scrolling until arriving to the correct one. A recent study found that a physical key-grid is less dependent on visual attention than full-QWERTY [25]. Previous work has studied the use of a hand-held cellphone for text messaging while driving in a simulated environment using T9 method [4]. They showed that the use of the cellphone while driving impacted driving performance negatively.

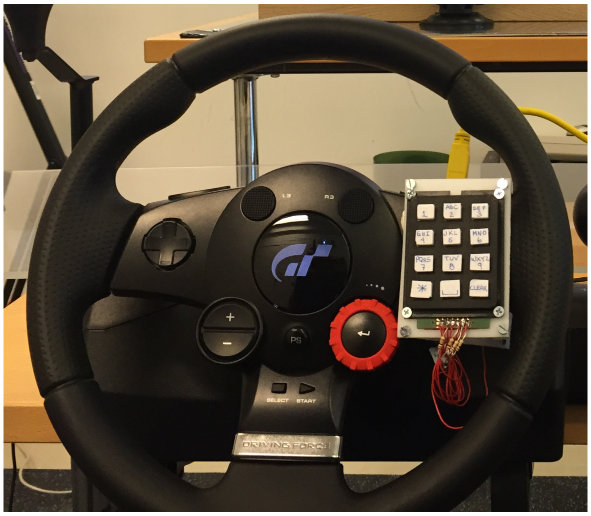

Figure 2. Prototype design of the T9 integrated to the steering wheel, which was used in the evaluation study.

However, in the study participants input text and observed the output while holding the phone in their hands, and the device was not solely used as an input mechanism but also for output.

Based on previous research, we expect that the combination of T9 and HUD will decrease drivers' glance time off road and improves driving performance while typing compared to the most popular means currently available: in-car touchscreen keyboard. WPM and error rates as well as the experienced workload are expected to be on par with a touchscreen keyboard while the vehicle is on the move.

T9+HUD PROTOTYPE DESIGN

We use a T9 device with 12 physical buttons with small gaps in-between the keys (see Figure 2). The first eight keys starting from the second key in the first row contain a sequence of three letters from the alphabet beginning with "abc". The first key of the grid contains punctuation marks. In the last row there are keys for switching between the suggested words, inputting a space, and entering the current word or phrase into the system. The physical buttons provide tactile feedback while exploring and pressing them and allows an experienced typist to type without looking at them.

The steering wheel was the Driving Force GT of Logitech. The front right side of the steering wheel was chosen for the location of T9 in order to serve the right-handed majority of the driver population. The physical device was connected to an Arduino Board, which at the same time was plugged to a laptop computer running the T9 algorithm and projecting the words to the screen.

For the experiment, we implemented an inexpensive HUD by placing a tablet (iPad Air 2) on a dashboard stand facing the windshield (see Figure 3). It projected to the glass a white text line (Georgia 70 pixel) on black background. This text was located on the drivers' sight-line, allowing them to keep their eyes close to the road. Also, the text was reflected by a film attached to the glass. This improved the sharpness of the projection and removed the double image generated by the double glass layer. Furthermore, the brightness level of the tablet was set to maximum.

METHOD

We evaluated T9+HUD in an experimental study in a driving simulator. Previous studies have used similar setup and the same driving simulator software [10]. Furthermore, despite empirical studies show that a driving simulator may have low resemblance with real-world driving, even low-fidelity simulators can have high predictive and comparative validity [26]. Also, driving simulators are routinely used as a research tool in traffic psychology [26].

In the transcription task, the participants listened to a sentence from a speech synthesizer, then typed it and proceeded to listen to the next one. Because this is the first study looking at T9+HUD, we decided not to employ synchronization (between texting events and road events), but randomize texting prompts. The participants carried out texting both while driving and while stationary. In the study, T9+HUD was compared to a baseline design [13]: A touch screen device using a regular QWERTY keyboard and embedded into the center console of the car (Figure 5). We report several dependent variables, including lane keeping performance, text entry performance (words per minute, errors), off-road glance durations, and experienced task workload.

Participants

Sixteen subjects participated in the study (10 male, 6 female), in the age range of 21 to 48 (M = 28.1, SD = 7.2). All of them had normal or corrected-to-normal vision. They were experienced or intermediate drivers with at least 2 and up to 19 years of driving experience. They were advanced or very advanced English speakers. Moreover, all were right-handed.

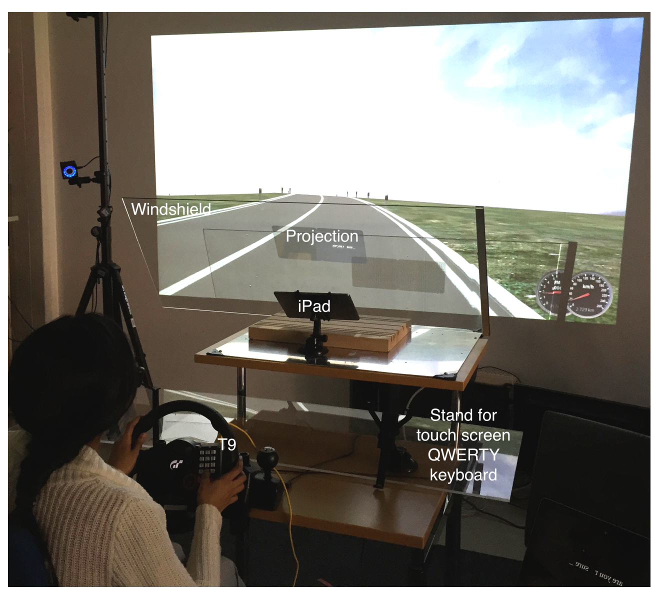

Figure 3. Participant and the driving simulator during the experiment.

Materials

The T9+HUD setup is as described above. The driving simulation was done with OpenDS software [20], the simulated road image (2.5 by 1.30 m) was projected to a wall using a Full HD Acer Projector (H7550BD) (see Figure 4). The road was a closed circuit, with two intersections, two long gentle curves both (right and left), four harsh curves to the right and two to the left. The road lanes were divided by a white lane marking. Driving was done on the right lane and the participant shared the road with six cars and one bus, but there was no interaction between them. Participants drove with automatic gear shift. The windshield (130 cm by 85 cm), positioned one meter away from the wall and on top of a table, was made with a quarter inch thick glass, with a 70 degrees tilt.

The steering wheel (Driving Force GT Logitech Steering Wheel) was placed at a distance of 88 cm (measured from the top of the wheel) from the windshield. Forty-six cm to the right away from the wheel and on another stand was a second tablet. A camera(Microsoft LifeCam HD-3000) was located right in front of the participant for eye tracking measurements. A Martela James chair was placed next to the table as the drivers seat, and it's height was adjusted to 40 cm. Finally, the pedals were on the floor at a convenient position for the participants. The study was run in a closed dark room.

Experimental Design and Dependent Variables

The study followed a 2 x 2 within-subject design with two Tasks (Driving, Stationary) and two Input Methods (touch screen QWERTY, T9) as independent variables. The order of both variables was counterbalanced. The order of the sentences for each task was randomized by sampling from a pool of 160 sentences.

The dependent variables measured were: *words per minute (WPM)* [29, 37], *error rate* [30], *lane deviations* (an excursion of at least half of the car to the right or left side of the right lane was manually scored frame-by-frame from video) [24, 17, 32], *glance time off road (%)* [9, 33, 8] (defined after the SAEJ-2396 standard [28]: a glance begins when the driver starts to shift the gaze (i.e., pupils) towards the keyboard, and ends when the gaze is back on the driving scene, these were measured from a sample of video recordings), and *experienced*

Figure 4. Road image, with speed indicator and line division.

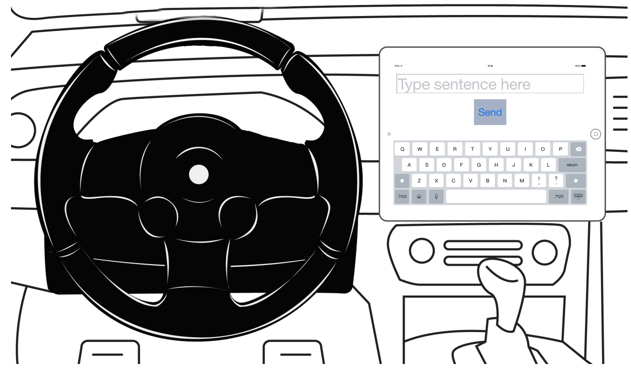

Figure 5. The baseline design had a touchscreen display integrated to the central stack. This design is used by Tesla's cars and is becoming increasingly common.

task workload (evaluated with the NASA-TLX questionnaire) [11]. The questionnaire was supplied at the end of each task.

Task and Procedure

In each task, participants heard a series of sentences, repeated each to ensure correct understanding and to avoid unwanted mistakes. They typed words to form a sentence, followed by holding the space key for one second to input it in the system, next a new sentence was played and the process was repeated. The goal was to input as correctly as possible at the same time keeping a fast typing pace. The driving task goal was to keep their own lane and speed below 60 km/h.

Participants were instructed to give priority to the driving task. Task conditions were as follows: the touch screen QWERTY keyboard design was used in stationary mode(speed at 0 km/h) with the right hand. The T9 was used with the right hand, as well. The sentences were sampled from the Enron Mobile Email Dataset (a group of mobile email sentences written by existing users on actual mobile devices) [35] and were played using a speech synthesizer. Sentences had lengths in the range of 9 to 62 characters with a mean of 26 characters.

Participants had 10 sentences to practice, followed by 30 sentences in the actual experiment for each condition. A total of 160 sentences were used in the 4 tasks.

RESULTS

Data was processed as following: to compute WPM we calculated a mean value of the total number of sentences input during each task. Error rates where determined using Damerau-Levenshtein distanace, which states the count of minimum number of operations needed to transform one string into another. Lane deviations were obtained per driving task per participant. Glance time off road was computed by measuring the number of video frames in each glance. A total glance time was calculated for each sentence. Finally, a mean experienced task workload was calculated per study task.

Words per minute

WPM scores were subjected to a repeated measures ANOVA having two levels of *Input Method* (T9+HUD, touch screen QWERTY keyboard) and two levels of *Driving Condition* (Driving, Stationary).

The main effect of Input Method yielded an *F*-score of *F*(1,15) = 25.867, *p* <.001, η_p^2 = .633, indicating that the mean score was significantly greater for the touch screen QWERTY keyboard (*M* = 29, *SD* = 3.61) than for T9+HUD (*M* = 21, *SD* = 3.31). The main effect of Driving Condition yielded an *F*-score of *F*(1,15) = 248.383, *p* <.001, η_p^2 = .943, indicating that the mean score was significantly lower when driving (*M* = 16, *SD* = 2.90) than in stationary mode (*M* = 25, *SD* = 2.77). However, there was also a significant interaction effect between Input Method and Driving Condition, F(1,15) = 42.355, p <.001, η_p^2 = .738. Figure 6) illustrates that the difference in WPM between the Input Methods was significant only in the stationary mode.

Error rate

Error rate scores were subjected to an ANOVA having two levels of *Input Method* (T9+HUD, touch screen QWERTY keyboard) and two levels of *Driving Condition* (Driving, Stationary).

The main effect of Input Method yielded an *F*-score of *F*(1,15) = 4.596, *p* <0.05, η_p^2 = .235, indicating that the mean score was significantly smaller for the touch screen QWERTY keyboard (*M* = 1.05, *SD* = .75) than for T9+HUD (*M* = 1.54, *SD* = 1.0). The main effect of Driving Condition yielded an *F*-score of *F*(1,15) = 5.123, *p* <0.05, η_p^2 = .255, indicating that the mean score was significantly lower in the stationary mode (*M* = 1.30, *SD* = .63) than in driving mode (*M* = 1.64, *SD* = .72). There was no significant difference between the input methods in error rates while driving. Also, there was no significant interaction effect between Input Method and Driving Condition, *F*(1,15) = .007 (Figure 7).

Lane deviations

T9+HUD led to considerably fewer lane deviations than the touch screen QWERTY keyboard (Figure 8). A repeated measures ANOVA was conducted to analyze the effects of Trial (baseline driving, QWERTY, T9+HUD) on lane deviations. There was a significant main effect of Trial on lane deviations, *F*(2,30) = 12.898, *p* <.001, η_p^2 = .462. Pairwise comparisons reveal that there were significant differences in lane deviations between QWERTY and baseline (mean difference 16.75, *p* = .002, 95%CI[7.39,26.10]) and between QWERTY and T9+HUD (mean difference 13.31, *p* = .003, 95%CI[5.23,21.40]). There was no significant difference between T9+HUD and baseline driving (mean difference 3.44, *p* = 0.055).

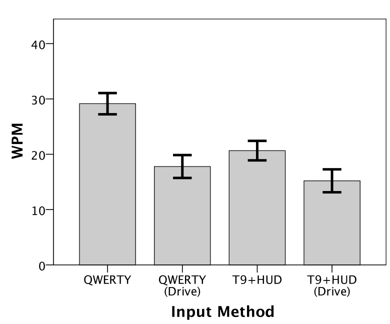

Figure 6. Typing speed when stationary vs. driving (95% CIs)

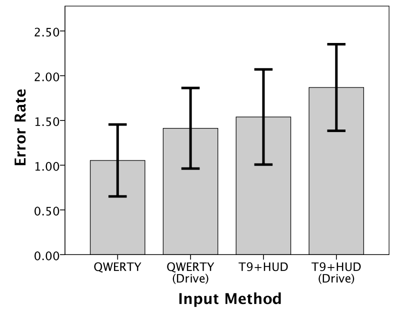

Figure 7. Error Rate when stationary vs. driving (95% CIs)

Glance Time Off Road

T9+HUD also shows much lower percentage of glance time off road than with QWERTY (Figure 9). A paired-samples t-test suggests a significant difference in glance time off road between the touch screen QWERTY keyboard and T9+HUD (t(4) = 6.132, *p* <0.05), 95%CI [26.83, 71.21], *d* = 3.82, *r* = 0.89. The average glance time off road percentage was 76.41 for the touch screen QWERTY keyboard (*SD* = 8.64), whereas for T9+HUD it was 27.39 (*SD* = 15.99).

Workload

Both input methods were associated with similar workload levels (Figure 10). Subjective workload scores were subjected to an ANOVA having two levels of *Input Method* (T9+HUD, touch screen QWERTY keyboard) and two levels of *Driving Condition* (Driving, Stationary).

The main effect of Input Method yielded an *F*-score of *F*(1,15) = 1.835, *p* = .196, indicating statistically insignificant effect. The main effect of Driving Condition yielded an *F*-score of *F*(1,15) = 28.695, *p* <0.05, η_p^2 = .657, indicating that the mean score was significantly lower in the stationary mode (*M* = 27, *SD* = 11.53) than in the driving mode (*M* = 45, *SD* = 18.97). No significant interaction effects between the independent variables were observed.

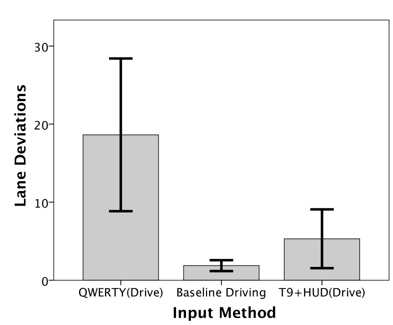

Figure 8. Lane deviations in the driving-only and driving-and-typing conditions (95% CIs)

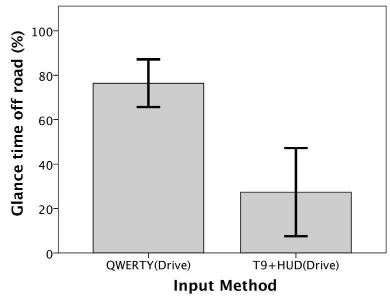

Figure 9. Glance time off road (%)

DISCUSSION

The empirical results show that T9+HUD allows drivers to maintain more visual attention on the road and have less lane deviations than a QWERTY touchscreen design, that is nowadays typical in modern cars. In comparison to the dashboard-mounted touchscreen device, T9+HUD reached nearly equal text entry rates, error rates, and similar levels of experienced workload while driving, but reduced lane deviations by 70%. Also, lane-keeping performance with T9+HUD was not statistically different from baseline driving. T9+HUD decreased glance time on keyboard by 64% in comparison to the touch screen QWERTY. There is evidence suggesting that T9 keypad can demand low attention after sufficient practice [25]. Despite the finding that T9+HUD is slower when typing stationary, the difference was insignificant while driving. This is understandable as the touchscreen input had to be interrupted continuously by looking at the road.

When looking at the experimental design more carefully, one can notice that there were actually three possible contributing factors of T9+HUD. The three factors were 1) keyboard (T9 vs. QWERTY on touchscreen), 2) output (HUD vs. center console touchscreen), and 3) hand position: both hands versus one hand on the steering wheel. The effects on glance time off road should be studied separately. Based on the current study, we cannot conclude which of the factors affected driving performance and how much.

The observed advantages of T9+HUD could, however, be easily undermined if either the keyboard or the output display would demand more attention to be directed off road. This would be the case, if the HUD was replaced with a head-down display, such as in [4], or if the T9 was replaced with a touchscreen keyboard. Typing with a touchscreen keyboard has been shown to involve high visual demands (e.g., [25]), regardless of the position of the output display. This means it is the combination of T9 and HUD that enabled the improved driving performance. The location of the input device on the steering wheel could be observed as an advantage, since it allows drivers to always keep their hands on the wheel and avoid the effort of stretching the arm to reach the other keyboard positioned on the dashboard.

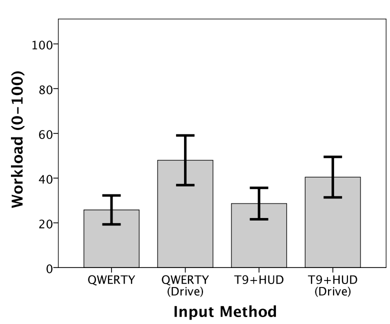

Figure 10. NASA-TLX workload comparison (95% CIs)

Our solution is not intended for encouraging anyone to text while driving. Instead, our study shows that for those drivers who already text (or type text into in-car infotainment systems), it is possible to decrease the distraction effects of the activity by designing safer methods for text entry while driving. However we are aware that there is a potential risk that this solution might increase the action of text while driving.

Limitations and Future Work

The results call for more attention to alternative text entry methods. In future work, the findings should be replicated with larger and more representative driver samples, including elderly drivers. In addition, the benefits and possible downsides of the T9+HUD design should be studied with more realistic typing tasks and driving environments. Furthermore, drivers' performance with T9+HUD tasks on standard in-car glance duration criteria, such as the ones set by the National Highway Traffic Safety Administration (2013) [2] should be evaluated. The current study does not reveal if typing with T9+HUD is safe while driving in real traffic conditions, it indicates us only that its harmful effects on the measured variables are significantly smaller than while typing with touchscreen QWERTY keyboard.

Gaze on the HUD does not necessarily mean that the driver's attention is on the road. Reaction times for unexpected events while typing should be carefully investigated. Percent Road Centre (PRC) [36] is a measure of *attention capture* by the HUD that should be used in future studies. It would reveal if the driver's functional field of view decreases significantly compared to baseline driving when typing with the HUD. Also, detection response tasks should be considered for future experiment replications in order to assess if drivers miss peripheral targets while interacting with HUD typing tasks. Finally, our study was executed with a simple driving scenario for control purposes, but we suggest that more complex road environments and driving scenarios should be studied in future research.

CONCLUSION

While more research is needed, the results of this study indicate that it may be possible to improve the safety of in-car typing with a text entry method that combines an HUD and a small physical keypad integrated into the steering wheel.

ACKNOWLEDGMENTS

The study followed the ethical practices and legislation of the site of research. We will provide the code for the T9+HUD and a description of the setup on the project home page. This work was funded by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 637991) and the Academy of Finland project COMPUTED.

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