Subjective Contribution of Vibrotactile Modality in Addition to or Instead of Auditory Modality for Takeover Notification in an Autonomous Vehicle

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***Abstract*—In future autonomous vehicles, drivers will be allowed to do anything else but driving. However, those autonomous cars may call the driver back to driving if all requirements for autonomous navigation are not met. Therefore, a call back sequence must be designed. The call back sequence must be efficient, as well as satisfying, in order not to annihilate the benefit of autonomous driving. Recent studies show the interest of using tactile channel for in-vehicle interfaces. In this study, we investigate the subjective contribution of vibrotactile signal instead or in addition to auditory modality for takeover sequences in an autonomous vehicle. We conducted a simulator survey on 41 subjects. The participants had to score their satisfaction and to evaluate the efficiency and some hedonic aspects of the sequence. According to the results, we recommend a multimodal signal for the takeover sequences in an autonomous vehicle. This must be confirmed with an evaluation of objective efficiency of the signal.**

Keywords- Interface design; Vibrotactile; Autonomous driving.

I. INTRODUCTION

During autonomous navigation phases, drivers can do anything they want but sleeping. Their attention may not be triggered by signals that may appear. According to NHTSA, level 3 of automation called “Limited Safe Driving Automation”, implies that drivers must remain available to intervene with comfortable transition time if all conditions necessary to allow autonomous navigation are not met (e.g., the vehicle leaves highway, etc.) [1]. To ensure a safe and comfortable transition, a sequence of call back signals must be designed. To date, there are no standards about those call back signals.

Traditionally in an automobile environment, auditory and visual signals are used to convey information to the driver. However, many applications could benefit by using vibrations in the seat to transmit information [2], for instance lane departure warning [3][4], collision warning [4][5], hypovigilance alert [6], situation awareness [7], navigation [6][8], notifications [6][9] and even relaxing activities [10].

Several studies reported pros & cons of using tactile modality in vehicle (see [11] for a review). Even though no reason is given, this modality is rarely used in cars [10][12]. According to Wickens’ multiple resource theories [13], tactile channel can convey information while auditory and visual channels are overloaded [14][15]. Firstly, a few studies reported that tactile modality has good alert properties. For instance, the reaction time decreases for a tactile or an auditory collision warning compared to a visual warning or no warning, or even an auditory warning when the driver is involved in an oral conversation [5][16]. Moreover, the tactile modality decreases the reaction time compared to the auditory modality for a navigation system and a Bluetooth hand-free system [6]. Secondly, depending on the context, the properties inherent to tactile modality can be relevant. For instance, tactile interactions are private, and subtle [17]. Furthermore, in most of the cases, it does not interrupt the current activity, which could let the subject choose the exact moment of interruption, and therefore reduce frustration.

There are also some practical limitations of using tactile modality. Tactile interfaces can convey limited information. Yet studies showed the possibility to recognize 7 haptic icons during a high visual load task [18]. The best compromise between number of possible in-vehicle tactile alerts, and efficiency and adequacy of reaction, could be with only 3 different tactile alerts [19]. Finally, there are some situations that may adversely affect perception of tactile warning. Some drivers are wearing thick clothes, which could affect their perception of vibrotactile stimuli in the seat [2] even though this effect may be relatively low [20]. Also, ambient vibration could mask the signal’s vibrations [21][22]. Recent studies show the influence of attention, movement [23][24] and back pain [25] on tactile sensation.

Acceptability studies show mitigate results for vibrotactile interfaces. For a collision warning, it has better scored including on items like “trust”, “overall benefit to driving” or “annoyance” [4]. Auditory warnings was clearly better accepted than tactile warning in the seat for a lane departure warning [3]. The subjective workload associated with a navigation system, and hand-free system were scored higher, and items like “quick to understand” or “easy to learn” were scored lower for tactile modality compared to auditory. This can adversely affect the acceptability of a tactile signal. The satisfaction evaluation may be influenced by the innovative nature of tactile feedback in the seat [6]. The meaning of the signal and the context may also have a great influence on acceptability.

Multimodality is proposed to find a good compromise between efficiency and acceptability [26]. However, it has been shown to increase perceived urgency [8][27].

In brief, tactile modality shows interesting performances for in-vehicle interfaces, but it must be tested for each given application. In this paper, we focus on takeover notifications in autonomous vehicles.

At least two types of evaluations are necessary to choose the most appropriate modality [28]: objective evaluation, on the measured performance, and subjective measure on acceptability. This study focused on the second one: we aimed to evaluate the subjective contribution of vibrotactile modality instead of, or in addition to auditory modality during a takeover phase in an autonomous vehicle. Moreover, we investigated on the relevance of a reminder: a second notification when half of the allocated time to take over has passed.

To answer our problematic, we conducted a customer study, described in Section II. The results are presented in Section III and discussed in Section IV. Lastly, we give our recommendations and perspectives in Section V.

II. MATERIAL AND METHOD

To evaluate the signal in a realistic context, we conducted a customer survey in an autonomous driving simulated context.

A. *Products*

A takeover sequence, begins with a takeover notification one minute before the end of the autonomous driving mode. In our study, we used tactile modality, auditory modality or both.

1) *Tactile signal*

A haptic seat mock-up was created based on a commercialized seat (Renault, Espace 5). Several actuators were integrated in the seat backrest and cushion. The chosen actuators (voice-coil type, furnished by Lofelt) enable to independently set the frequency and the amplitude of the vibrotactile stimuli. Two preliminary studies were conducted before the present study: the first one aimed to define the right location of the actuators in the seat, and the second one aimed to define the pattern of the signal.

The locations of the actuators were chosen after a preliminary experiment for which eleven subjects participated. The participants of this first preliminary experiment were chosen to ensure a diversity of morphology in the panel. There were 6 men and 5 women. Height was from 147 to 200cm (mean: 176; sd: 13), and Body Mass Index (BMI) from 18.4 to 30 kg/m² (mean: 23.3; sd: 4). The actuators' locations allow an effective and acceptable perception of the vibration of each actuator, for all participants. Because we wanted to have a symmetric signal, and because it was not acceptable to place the actuators under the spine, they were set in two columns.

The tactile signal was designed after a second preliminary study measuring detection and acceptability of 16 signals. Those signals were designed based on a design of experiments, which enabled us to model detection rate and acceptability depending on signal characteristics. It was conducted on a large panel: 80 participants from 30 to 75 year old (mean: 49; sd: 11), BMI from 17.7 to 53.5 kg/m² (mean: 26.2; sd: 5.4). This signal is above detection threshold and supposed to be well accepted (estimated satisfaction score: 8.3/10).

2) *Auditory signal*

In this study, auditory signals previously designed for partially autonomous driving studies [29] were used. We only used the signal designed for a takeover notification, which is the equivalent of the vibrotactile signal. The signal was previously used in a few customer studies and was never reported as disturbing.

3) *Takeover sequences*

Five different takeover sequences were tested (see Table 1). Three are composed by a single notification occurring 1 minute before the end of autonomous mode. The other two were composed by two notifications: the first notification occurring 1 minute before the end of autonomous mode, followed by a second notification when half of the time to take over has passed (Fig. 1). We used either vibrotactile signal, auditory signal or a combination of those two signals.

TABLE I. MODALITIES OF THE NOTIFICATIONS FOR EACH SEQUENCES

Sequence	First notification	Reminder
V	Vibrotactile	-
A	Auditory	-
V+A	Mixed	-
V + reminder A	Vibrotactile	Auditory
V + reminder V+A	Vibrotactile	Mixed

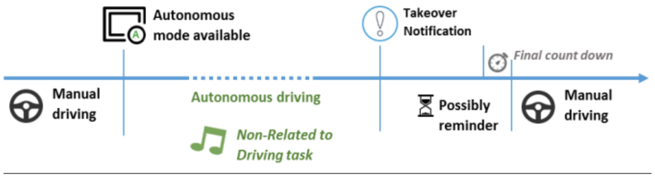

Figure 1. Driving trial with notification and possible reminder to takeover sequence.

B. *Simulation*

The study was conducted in a fixed-base simulator consisting of driver and passenger seats, steering wheel, and pedals (Fig. 2 a). The road was projected on a 60 inch screen (Samsung UE60D6500).Visual HMI (Human

Machine Interface) were disposed on two screens. The first one was a 15’’ screen corresponding to the dashboard (Fig. 2 b, Litemax®, SSD 1515 ENB G01). The second was a 10,4’’ touchscreen and corresponds to the central screen (Fig. 2 c, Litemax®, SLO1068 EGB I51). Visual interfaces related to autonomous system were developed to conduct autonomous driving studies at Renault. They remain the same for each takeover sequence. They continually display the state of the autonomous system (unavailable, available, activated, takeover notification, takeover required). The scenario was navigation on a highway road. The takeover notification was triggered by the experimenter without any scenario reason. The autonomous driving system used in this study was developed for an intern ergonomics study [30]. The simulation was generated using the simulation software SCANeR™ (v 1.4 ; Oktal), and the HMI were synchronized with the software RTMaps (v.4 ; Intempora).

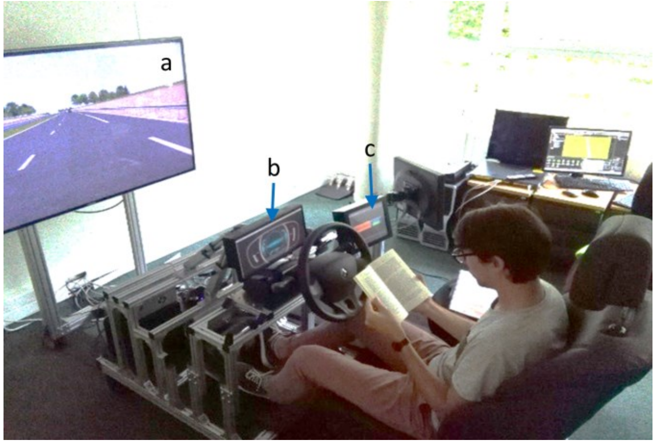

Figure 2 : Picture of the simulator

C. Observers

41 volunteers were recruited after an internet screening survey. This screening survey had two objectives:

- Recruit people without motion sickness and without negative opinion on testing autonomous driving. This way we avoid eventual rejection effect due to this particular technology.
- Selecting observers by the activity they declared they want to do during autonomous phases: observers had to choose an activity among three before the test: reading on a hard copy, working or watching a movie. We tried to form three equivalent groups of people performing those three activities: 15 participants were reading, 15 were watching a movie and 11 were working.

The participants had to bring their own device or book with them for the test. We assumed that letting them choose and provide their own activity would give them more interest for the non-related to driving task (NRD) that they would perform during the autonomous driving phases, and therefore make the situation closer to the implication they would have in real situations.

The volunteers were all employees working at *the Technocentre Renault (Guyan*court, France). There were 39 males and only 2 females from 21 to 60 years old (mean: 40; sd: 12) and their body mass index varied from 14,5 to 32 kg/m² (mean: 21; sd:4). They were unaware of the nature of the research, except the fact that it deals with autonomous driving.

D. Procedure

First of all, the autonomous driving HMI were explained to participants. Moreover, the autonomous driving interfaces were presented. The experimenter explained that when the first takeover notification rings, there is 1 minute left to takeover. He also explained that driver safety is ensured by the system anyway, even if the driver does not take over on time.

After a familiarization phase with the autonomous driving HMI and with the simulator, the test procedure was explained to the participants.

The session consisted of five tests. For each test, the participant started to drive, engaged the autonomous mode, focused on a “non-related to driving” task, and then, resumed the driving after the takeover signal of the current test.

The current call back sequence was played before each test in order to make the subject identify the takeover notification.

After each sequence, the participants had to fill a survey with a global satisfaction score and to score 9 adjectives relative to hedonic evaluation (“pleasant”, “soothing”, “stressful”, “frustrating”, and “disturbing”) and to perceived efficiency (“noticeable”, “stimulating”, “clear” and “efficient”).

The test order was balanced among participants, using a Latin square design: each sequence was tested an equal number of times at a given rank.

The test took about 1 hour per participant. The experiment lasted one month during the summer of 2016.

III. RESULTS

As the 41 subjects evaluated the 5 different sequences, there were 205 observations.

A. Satisfaction scores

We performed an analysis of variance (ANOVA) of the satisfaction score with sequence, NRD task and presentation rank as explicative variables. The sequence does have a significant influence on satisfaction but NRD task and presentation rank do not (Table 2).

There was no significant difference between the two unimodal sequences. The two unimodal sequences were worse scored than bimodal sequences. The reminder does not have any significant effect (Fig. 3).

TABLE II. RESULTS OF THE ANOVA ON THE SATISFACTION SCORES

Source	DoF	F	Pr > F
Rank	4, 194	0,805	0,523
Sequence	4, 194	6,685	< 0,0001
NRD task	2, 194	0,028	0,972

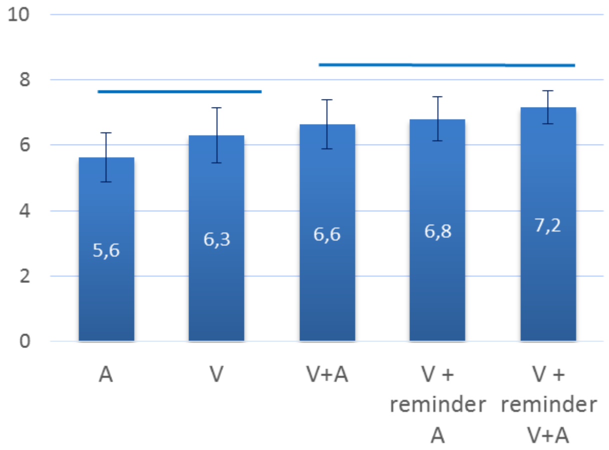

Figure 3. Mean satisfaction scores and Bonferroni pairwise comparison tests (α=0.05).

B. *Adjectives*

For each adjective, a one-way ANOVA was performed with sequence, NRD task, presentation rank and the interaction sequence*NRD task as explicative variables (Table 3), followed by a Bonferroni pairwise comparisons test (α=0.05).

TABLE III. RESULTS OF THE ANOVA ON THE ADJECTIVES

	Perceived efficiency				Hedonic evaluation				
	Noticeable	Stimulating	Clear	Efficient	Pleasant	Soothing	Stressful	Frustrating	Disturbing
$F_{(18, 186)}$	6,44	5,16	3,74	4,27	1,09	0,85	1,02	1,66	0,91
Pr > F	< 0,01	< 0,01	< 0,01	< 0,01	0,37	0,63	0,44	0,05	0,57
Sequence	23,31	17,93	10,70	13,81	1,67	1,62	1,43	0,34	2,44
	< 0,01	< 0,01	< 0,01	< 0,01	0,16	0,17	0,22	0,85	0,05
NRD-Task	2,36	4,01	4,74	4,08	1,25	1,05	1,57	11,29	1,61
	0,10	0,02	0,01	0,02	0,29	0,35	0,21	< 0,01	0,20
Rank	2,03	0,45	1,47	0,92	0,43	0,45	0,80	0,12	0,29
	0,09	0,77	0,21	0,45	0,79	0,78	0,53	0,97	0,89
Seq. * NRD-task	0,64	0,68	0,71	0,94	1,15	0,52	0,82	0,64	0,33
	0,74	0,71	0,68	0,49	0,33	0,84	0,58	0,74	0,95

The interaction type of sequence*NRD task and presentation rank had no effect on any adjective. In other words, the effect of the sequence was not dependent on the NRD task, and vice-versa.

1) *Influence of the sequence*

The sequence had a significant effect on the four adjectives about perceived efficiency (Fig. 4). For each, the score of the sequence with a single auditory signal was lower than the score of the other sequences. The reminder had no effect compared to single vibrotactile notification or a mixed single notification.

The adjectives "pleasant", "soothing", "stressful", "frustrating" and "disturbing" could not be explained with the chosen explicative variables.

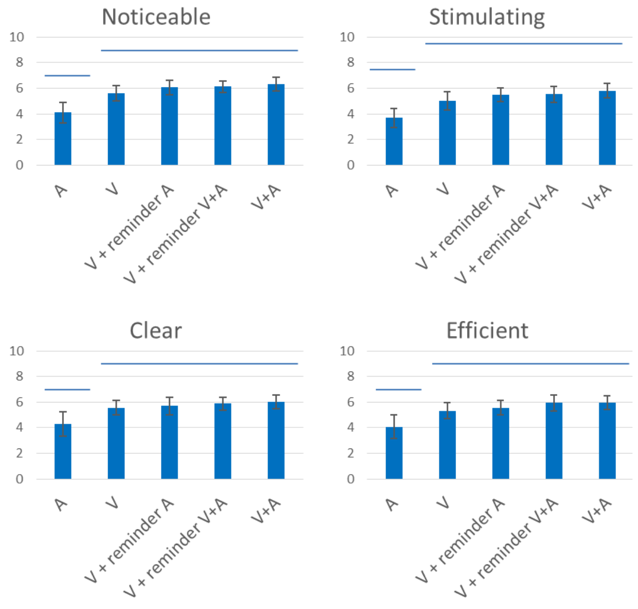

Figure 4 : Mean scores by sequences for the four adjectives related to perceived intensity. Bars correspond to a Bonferroni test (α=5%).

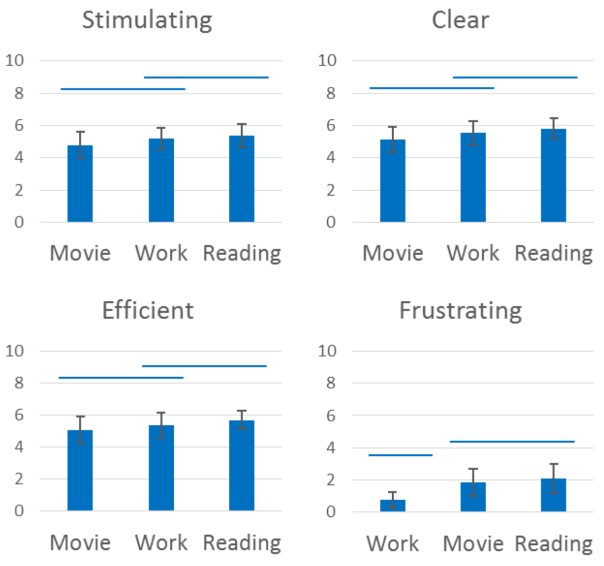

Figure 5: Mean scores by activity for 3 adjectives related to perceived efficiency and "frustrating". Bars correspond to a Bonferroni test (α=5%).

2) *Influence of the NRD task*

The NRD task had a significant influence on three adjectives about perceived efficiency: “stimulating”, “clear” and “efficient” (Fig. 5). For each adjective, the scores given by participants who were watching a movie were lower than the scores given by those reading.

Moreover, the NRD task had an influence on one adjective related with hedonic evaluation: “frustrating”. The participants who were working declared to be less frustrated than those who were reading a book or watching a movie.

IV. DISCUSSION AND LIMITATIONS

41 people participated to the study, who were divided in three group of activity. Those groups were composed by at least 11 participants. This was sufficient to find significant results. Increasing the number of participant could enhance the differences.

A. *Effect of the modalites used in the sequence*

Previous studies show that vibrotactile modality has mitigate results in terms of satisfaction. The hedonic properties of a signal seem to be dependent on the application. In our case, i.e., takeover phase in an autonomous vehicle, the vibrotactile modality in combination with the auditory modality increases the satisfaction score. The presence of a reminder has no effect compared to a mixed single notification. Our data show no differences for the satisfaction scores between the tactile signal and the auditory signal. Those results may not be generalized to other tactile and auditory signals because the two evaluated signals were previously optimized.

The vibrotactile modality in addition to, or instead of auditory modality increases the perceived efficiency. Most of the study show that tactile and auditory modality have comparable efficiency, unless in some cases including the driver involved in an oral conversation, where tactile alert has been shown to be more efficient [16]. We could assume that auditory background disturbs the efficiency of an auditory signal, but in our study, the interaction sequence*NRD task has no significant effect on the adjectives. Another explanation of the better perceived efficiency of tactile modality is the low familiarity of the participants with this kind of signal, whereas the automobile environment is full of auditory signals.

B. *Effect of the non related to driving task*

We found that watching a movie decreases the score on three adjectives related to efficiency. Two reasons could explain this. First, the auditory background of the movie disturbs the detection of the signals, regardless of their modality. Then the involvement of the subject in their task may be more important for those watching a movie than those working, which is consistent with the greater frustration of the first compared to the second.

C. *Limitations*

The 41 participants were mainly males with a low body mass index. The results should be validated with a more diversified panel, for instance, in terms of gender, age, body mass index.

As those results were obtained in a low fidelity simulator, a validation in real driving situation, taking into account vibro-acoustical background, as well as real risk perception for the driver is needed. To evaluate the takeover sequence, it is crucial, that the participant feels in the position of the driver. Because, we did not have an autonomous vehicle prototype for the experimentation, we conducted the study in a simulator.

It could also be interesting to reproduce the study with others tactile or auditory signals to evaluate the influence of the nature of the signal.

V. CONCLUSION

This paper focuses on the subjective evaluation of tactile modality in addition to, or instead of auditory modality during the takeover sequences in an autonomous vehicle. According to our results, we recommend the combination of vibro-tactile and auditory modality to improve the subject’s satisfaction as well as the perceived efficiency of the takeover sequence.

Future studies must investigate on the objective efficiency of the five sequences, such as time to take over, situation awareness at takeover, in order to link the objective and the subjective evaluations.

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