The Design of a Segway AR-Tactile Navigation System

Ming Li, Lars Mahnkopf, Leif Kobbelt

Computer Graphics Group
RWTH Aachen University
Aachen, Germany
http://www.graphics.rwth-aachen.de

Abstract. A Segway is often used to transport a user across mid range distances in urban environments. It has more degrees of freedom than car/bike and is faster than pedestrian. However a navigation system designed for it has not been researched. The existing navigation systems are adapted for car drivers or pedestrians. Using such systems on the Segway can increase the driver's cognitive workload and generate safety risks. In this paper, we present a Segway AR-Tactile navigation system, in which we visualize the route through an Augmented Reality interface displayed by a mobile phone. The turning instructions are presented to the driver via vibro-tactile actuators attached to the handlebar. Multiple vibro-tactile patterns provide navigation instructions. We evaluate the system in real traffic and an artificial environment. Our results show the AR interface reduces users' subjective workload significantly. The vibro-tactile patterns can be perceived correctly and greatly improve the driving performance.

Keywords: Segway, Navigation, Augmented Reality, Vibro-Tactile, Feedback modalities, Real Traffic, Evaluation

1 Introduction

The Segway Personal Transporter is a two wheeled, self balancing vehicle which can transport the user across mid range distances in urban environments (indoor and outdoor). Due to its mobility and compact size, it is widely used in city touring, airport, security patrol, theme park, gaming, etc. By 2010, it was estimated that 80,000 Segways were in use worldwide [4].

To use the Segway in an unfamiliar terrain, it would be very helpful to have a navigation system to guide the user to the destination, e.g. in a city guide scenario a user drives a Segway in a foreign city. However, the navigation system adapted to the Segway has not been investigated yet. The existing systems are designed for car drivers, pedestrians, and bicycle riders, using visual, auditory or tactile information. The traditional commercial in-vehicle navigation system (TVN) is not suitable for the Segway. Normally the route is presented via a 2D Map View (in orthogonal or perspective view, see Fig. 1(a)) and turn-by-turn audio instructions. When using a navigation system on the Segway, the interactive

(a) Map Interface [2].

(b) AR Interface.

Fig. 1. Navigation Interfaces.

task can be classified into primary task (observing traffic and controlling the Segway) and the secondary task (interacting with the navigation information). Unlike car drivers, the listening condition of the Segway drivers is greatly influenced by the surrounding environment. Ambient noise, from wind and traffic, seriously affects the perception of audio instructions. Using a headphone/earplug could improve the auditory perception, but the driver loses the environment awareness which could result in potential accidents and it is prohibited by the law in most countries. The 2D Map View, as an abstract representation of the environment, requires the driver to mentally project the route into the real world, which visually distracts the driver from the primary task and also increases the cognitive workload [16, 12]. Therefore the driver has to concentrate visually and auditorily more on the secondary task than the primary task. Since the driver has a limited information processing capacity, that would decrease his/her ability to complete the primary task [19].

In addition, the turning instructions of a navigation system needs to give the driver enough time for perceiving and interpreting. In TVN, the amount of time is customized for vehicles but not for the Segway. For example, if we assume a car moves with 50 km/h, a distance of 50 meters corresponds to 3.6 seconds. Assuming that an audio instruction takes 2 to 3 seconds, a turning instruction in a distance of 50 meters is too late. While for the Segway, since the maximum speed is limited to 20km/h, 50 meters takes about 9 seconds which is still enough for the reaction.

Pedestrian navigation systems are not suitable for the Segway either, because the map resource is collected for walking purpose, e.g. the road network includes staircases, one-way streets and pedestrian zones, where either a Segway can not access or the use of a Segway is forbidden.

Compared to the bicycle, the user experience is different when driving a Segway. It requires less physical effort to drive the Segway and the maximum speed is limited to 20 km/h. Furthermore, the Segway is more agile than the bicycle, e.g. it can rotate 180 degrees in place and it can move backward freely. Due to these differences, the existing research results for bicycle navigation can not be directly applied to the Segway.

In this paper we propose a GPS based Augmented Reality vibro-tactile navigation system for the Segway, which displays the route information in a graphical overlay to the real-world camera input during Segway driving. From the previous researches, the AR View enables drivers to keep high visual attention on the road [12]. Our goal is to investigate whether the same results also apply for the configuration we find on the Segway. We expect the AR view will generate less cognitive complexity than the 2D Map View. In order to further reduce the influence of the navigation task to the primary driving task, we migrate the turning instructions to the tactile channel instead of using the auditory channel, because the vibro-tactile is independent from ambient noise. Multiple turning instructions are encoded in vibro-patterns to deliver direction and distance information. The contribution of the paper is to explore the impact of AR navigation and vibro-tactile turning instructions on users' cognitive workload, preference and driving performance. A TVN is included in our experiment as a baseline for comparison, see Fig. 1(a). We conduct the user study in real traffic in order to get the actual driving experience, e.g. whether the vibration from the bumpy roads and the Segway itself affects the perception of vibro-tactile patterns. We propose two hypotheses.

1. Compared with the 2D-Map navigation interface in TVN, AR interface can reduce users' subjective workload.
2. The vibro-tactile turning instructions can be perceived by drivers clearly, and it improves their driving performance.

To support these hypotheses we design two user studies. The first one is an on-road test-drive to collect users' subjective rating about navigation system variants. The second study is a lane switching test in an artificial environment to measure users' reaction time for controlling the Segway when receiving audio or tactile instructions.

2 Related work

Jensen et al. [9] presented a study on the impact of different GPS based navigation systems to the car driving behavior and performance. They evaluated the audio, visual and audio-visual output of the navigation in real traffic. Their result showed that using the audio feedback could reduce the amount of eye-glances on the display and improved the driving performance. However, in the scenario of Segway driving, users' perception of the audio feedback is affected by the ambient noise. In our paper, a usability study of the audio feedback for the Segway navigation is done.

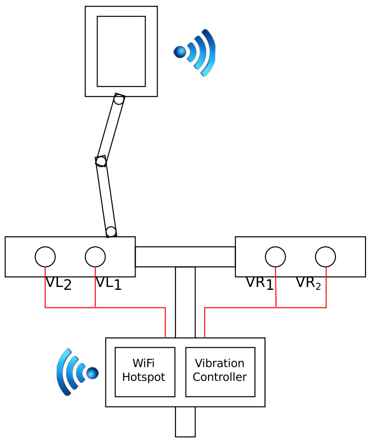
Previous work from Medenica et al. [12] indicated that AR navigation introduced less negative impact on car driving than traditional map navigation. In their work, the AR route is displayed on the windshield with a head-up display, which improved the driving safety and reduced the user's reaction time compared to the traditional in-car head-down display. However, the same configuration is not possible for a Segway. How to configure the AR display for the Segway driver and whether users prefer the AR display in this way need to be investigated. Wikitude Drive [3] is the first commercially available AR navigation system, but it is still designed for in-vehicle use and uses audio instructions. We are not aware of any evaluation comparing Wikitude Drive to TVN.

Some researchers proposed vibro-tactile displays for automobile navigation, where vibrators were integrated in the seat to deliver navigation instructions ([7], [6]). The results showed that the tactile navigation can improve the driving performance and reduce the cognitive work load. However such configuration is not practical for a Segway, since the Segway driver has to stand while driving. The contacting location with the Segway are only hands and feet. To exploring other vibro-tactile locations in vehicles, Kern et al. [10] embedded the vibro-tactile feedback into the steering wheel to give navigation instructions. Their results showed that the vibration patterns were ambiguous to users, since the vibration location on the wheel was hard to distinguish. Furthermore, the driver had to hold a certain area of the wheel to receive the tactile feedback, which could be uncomfortable due to different driving habits and situations. Unlike the steering wheel, the Segway driver always holds the grips while driving the Segway, so it is ideal to attach the actuators there. However, the proper vibration patterns, like strength, frequency, duration and users' acceptance, still need to be investigated. Boll et al. [5] introduced a vibro-tactile waist belt for the in-vehicle turn-by-turn navigation to reduce the driver's cognitive load. They presented a series of vibro-tactile patterns for turning instructions, where the number of repetition of discrete pulses corresponded to distance indicators. However, for the Segway driver the counting of pulses introduces extra mental workload which could reduce the driving performance. Additionally since the Segway speed is much slower than an automobile, it is unnecessary to present distance indicators beyond 100 meters (which takes 18 seconds at 20km/h speed).

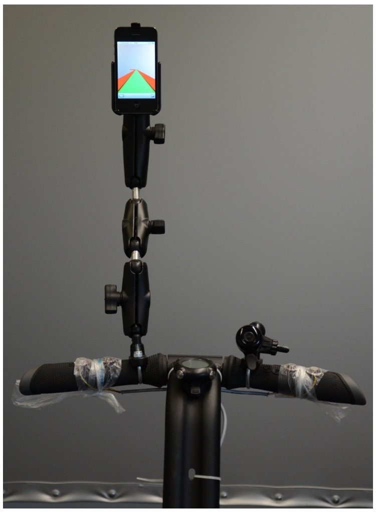
Pedestrian navigation using tactile feedback for turning instruction has been investigated as well. Pielot et al. [13] proposed a PocketNavigator which encoded turning instructions in vibration patterns. Srikulwong and O'Neill [17] suggested different vibration patterns to represent landmarks on a wearable device. Ross and Blasch [15] presented a shoulder-tapping wearable interface for pedestrian navigation. However, in the Segway scenario the perception of vibro-tactile patterns could be affected by the vibration induced by the bumpy road condition and the engine. The existing configurations and results of the pedestrian vibro-tactile navigation can not be directly applied to the Segway.

Poppinga et al. [14] introduced a tactile display as an orientation aids for the bicycle touring on a touristic island. They integrated two vibration actuators to the handlebars to indicate coarse direction information and announce points of interest. For an open area exploring tour, the cycling is more like leisure and fun. The requirements for the navigation efficiency are much lower than for in-city navigation, where we have dense street networks, environment pressure and traffic rules to obey. The orientation aids are not sufficient for a city navigation scenario. Additionally, the driving experience of the bicycle is different from the Segway, e.g. engine noise, standing pose, etc., the proper vibro-tactile patterns need to be found out.

3 Design and prototype



(a) Concept sketch



(b) Photo

Fig. 2. System configuration on the Segway handlebar. The mobile device displays the AR-View and sends turning instructions to the vibration controller via WLAN. Then the controller triggers the corresponding vibro-patterns.

There are several benefits from using AR display in navigation. The route information is immersed into the real world. It's unnecessary for the driver to mentally project the route from the 2D map into the environment. The driving performance therefore can be improved [12]. Moreover, the video-see-through display does not block the driver's view. When the driver glances at the display, he is not detached from the traffic. In addition, by using AR display extra information can be overlaid in another layer, which would be useful for scenarios like a city tour guide.

To avoid the influence of the ambient noise, we propose using the vibro-tactile feedback instead of using the audio feedback for turning instructions, which is similar to a shoulder-tapping system [15]. The turning instruction is delivered to the driver via the actuators mounted on the corresponding grip of the Segway. Different vibro-patterns are used to represent distance and direction hints.

We have implemented a prototype of our navigation system on the iOS platform. An iPhone4 is mounted on the Segway handlebar by adjustable arms. The height of the display is adjusted to the driver's eye level. Since we use the integrated camera of iPhone4, to have a better perspective view of the camera input, the back-facing camera needs to point to the heading direction. In the beginning of our design, we considered using different display devices, e.g. Head Mounted Display (HMD). But so far it has not been allowed by the traffic regulations to wear such an equipment while driving in the street, so we did not use the HMD in the current prototype.

On each grip we attach two vibrators [1] which are controlled by an Arduino Uno prototype board. The iPhone4 sends turning signals to Arduino via a stackable Wi-Fi module, see Fig. 2(a), 2(b). To absorb the shock from the Segway, we put a piece of sponge between the vibrator and the grip. For a better receiving of vibration signals, we compared the tactile perception on palm and finger tips, and found out the finger tips were more sensitive. Therefore, we attach the vibrators to the position of the grip under finger tips.

3.1 Navigation graphical interface

In the AR interface, we have a video layer and a graphical layer, see Fig 1(b). The user selects the starting point and the destination from a standard map view. Then a corresponding route is fetched from google map, which is a set of waypoints indicating geolocations (latitude, longitude and elevation). From these geolocations, a 3D representation of the route is created and rendered in the graphical layer. The color of the route is adjusted to increase the contrast. Furthermore the transparency of the route polygons is adjusted to avoid occluding on-ground traffic signs. To reduce the route complexity to the driver, only a certain range of the route is displayed. Additionally, when the user gets close to the next turning point, an arrow pointing to the correct turning direction will show as a turn-by-turn visual hint. When the driver goes to a wrong direction or reaches the destination a corresponding sign will appear.

3.2 Turning instruction feedback

We provide two turning instruction feedback, audio and vibro-tactile. The driver can choose the feedback type. Here we only explain the design of the vibro-patterns. Erp [8] suggested magnitude, frequency, temporal and location as primary parameters of tactile information coding. We can adjust the vibration temporal patterns and location patterns, while the frequency and magnitude are not applicable with the actuators we have used. The design of patterns should not conflict with the traditional navigation information and could be mapped to the physical reaction. Fig. 3 shows the 5 vibro-patterns. The temporal patterns indicate the distance information. Discrete pulses (felt less intensive) mean an event in distance. While a continuous vibration (felt more intensive) represents an event is very close. The location patterns describe the direction information. The vibration on the left (or right) grip means turning to that direction. The vibration on both sides corresponds to the destination instructions. A vibration interleaved on left-right grips for multiple times indicates a wrong heading direction.

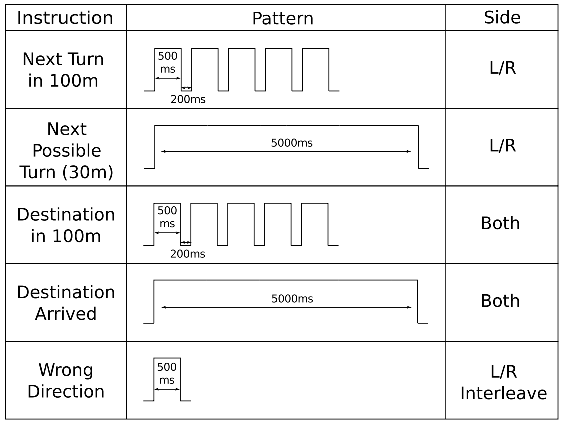


Fig. 3. Vibration patterns of navigation instructions.

In our initial studies, we compared continuous versus discrete vibrations, as proposed by [5], where the number of pulses indicated the distance (1: Turn-now, 2: Near, 3: Far and 4: Very-far). The users felt that the pulse counting even required more concentration on the tactile channel while driving the Segway, which was not preferred by users. Especially due to the Segway speed is much slower than the car speed, it is unnecessary to give an instruction beyond 100 meters, which takes 18 seconds in 20km/h speed. In our user study, we found the 2 level distance instructions are sufficient. The 100m instruction informed users to slow down and search for a street junction. The 30m instruction can be interpreted as "turn at the next possible turning point" and it was triggered 5 seconds before the turning point. Users had enough time to show the turning gesture (pointing the direction with the corresponding arm) and tilt the handlebar. Their comments indicated that the vibro-patterns were intuitive and easy to remember, even though the vibro-patterns were only introduced to them very shortly.

4 Setup and experiments

4.1 Study 1: Driving test in real traffic

Design The first study is a driving test in real traffic. The goal is to test users' subjective workload of different navigation methods in the real environment. The test area is around the campus and the road condition is good for driving the Segway. Three navigation conditions were compared:

Fig. 4. Part of the test area and route samples (Google Map, http://maps.google.de/)

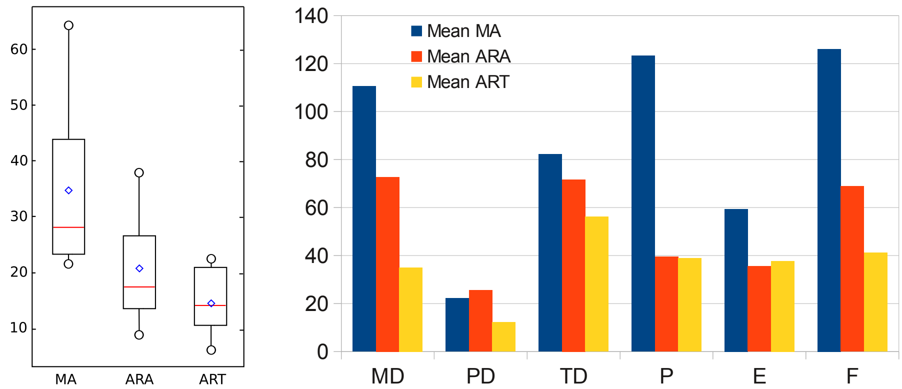
- **MA**: A TVN using Map plus Audio instructions [2]
- **ARA**: AR navigation interface plus Audio instructions
- **ART**: AR navigation interface plus vibro-tactile instructions

A commercially available in-vehicle navigator was used for comparison, which features a 2D map navigation interface (see Fig. 1(a)) and audio turning instructions. This navigator is widely used (more than 10 thousand downloads) and well accepted (rated 4.5 out of 5). Therefore it has the basic features of a TVN and fulfills our comparison requirements. All navigation conditions run on an iPhone mounted on the Segway. The iPhone speaker volume and the screen brightness are adjusted to maximum.

A within-subject-design is used, and each participant has to drive the Segway along 3 routes using different conditions respectively. The order of the conditions are counterbalanced for different participants. To avoid learning effects from the routes, we select them from different areas. Each route partly goes along a main street which has relatively dense traffic. The length of test routes varies from 2.1km to 2.5km and they contain 11 to 13 turning points, two samples are shown in Fig. 4.

Procedure In the beginning of the test, a Segway driving tutorial was given by the experimenter (E) on a parking lot, including driving basics, traffic rules of the Segway driving and a 1km trial in real traffic. After that, the real test started. E first introduced and demonstrated the navigation interface to the participant (P). Then E set the destination in the navigation system so that P did not know his destination in advance. P had to drive to the target following the navigation information, while E followed P by bike. When a destination was successfully reached, P had to answer a standard NASA-TLX questionnaire [11] to evaluate the subjective work load of that task. Further comments and problems encountered during the test drive was recorded as voice memos. The same procedure repeated 3 times using 3 conditions separately. P further rated the weights of the 6 aspects of NASA TLX. At the end, a post-test questionnaire was filled out. The questions are listed in Fig. 6. Overall each user test took about 80 to 90 minutes.

Samples The studies were conducted within two weeks. The wind speed varied from 5 to 15 km/h. 9 participants took part in this study: 2 females and 7 males, all students from the university, aged from 26 to 34. All participants had valid driver licences for the Segway and had normal or corrected eyesight. Most of them had none or very little on road Segway driving experience before, see Fig. 6.



(a) (b)

Fig. 5. NASA-TLX subjective workload rating. The left figure shows the overall workload rating (min-[1st quartile-median-3rd quartile]-max). Mean values are marked by blue diamond signs. The right figure presents the weighted rating of Mental Demand (MD), Physical Demand (PD), Temporal Demand (TD), Effort (E), Performance (P) and Frustration (F) under different navigation conditions.

Results *NASA-TLX*: Users' average rating were 34.9, 20.9 and 14.7 for MA, ARA and ART respectively, see Fig. 5(a). We used a one-way ANOVA to examine the effect of different navigation methods on users' subjective workload. We found a significant effect on the workload ($F_{2,24} = 8.114, p < 0.005$). Post-hoc comparisons indicated that participants had significantly less workload in ARA than MA ($p = 0.032$), as well in ART than MA ($p = 0.001$). But there were no difference between ARA and ART ($p > 0.05$). Comparing the 6 aspects of the NASA-TLX workload separately, see Fig. 5(b), the Mental Demand of ART was significantly lower than MA (mean value 35 and 110, $p = 0.032$). We also found significant difference in Performance among MA, ARA and ART (mean value 123.3, 39.4, and 38.9, $p < 0.01$). Users thought they performed better in ARA than MA ($p < 0.01$), and in ART than MA ($p < 0.01$), while there was no significant difference in performance between ARA and ART. Moreover, the frustration level of ART was significantly lower than MA (mean value 41.1 and 126.1, $p = 0.023$). *Notification Perception*: Users were asked if they can perceive

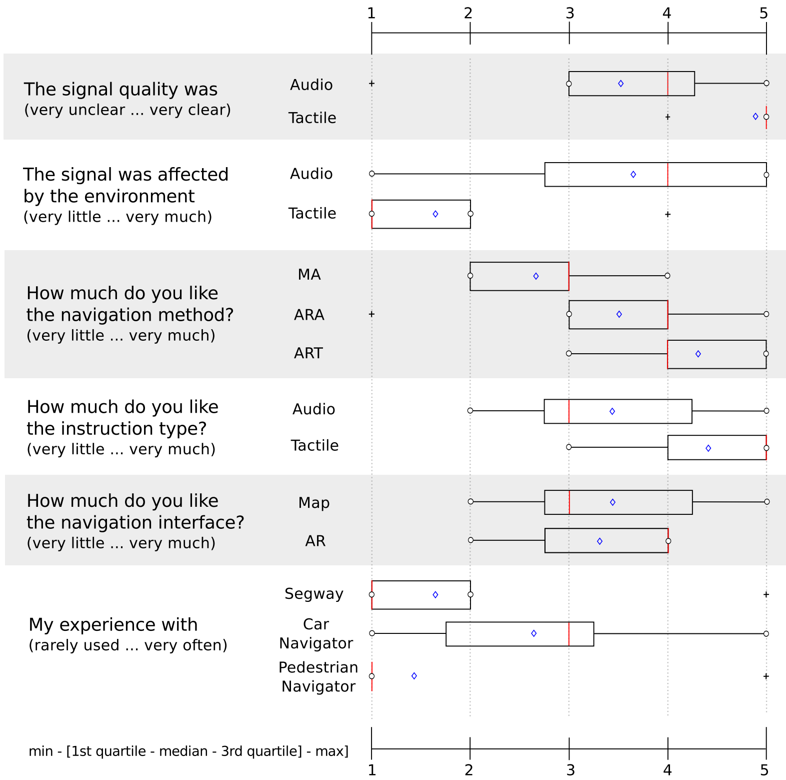


Fig. 6. Results of post-test questionnaire. Mean values are marked by blue diamond signs. Outliers are marked by black cross signs.

the instructions clearly (the signal quality question in Fig. 6). Mean values were 3.56 and 4.89 for Audio and Tactile respectively. A significant difference was found ($p = 0.0065$). From Fig. 6 we can see that the perception of the audio feedback was affected by different environments a lot, while the tactile feedback was more robust against environment changes.

Environment Influence: We asked users about the influence of the environment to the feedback signal, i.e. ambient noises to the audio quality and the Segway vibration to the vibro-patterns, see Fig. 6. Mean values were 3.67 and 1.67 for Audio and Tactile respectively. Obviously the tactile feedback was much less affected by the environment than the audio feedback.

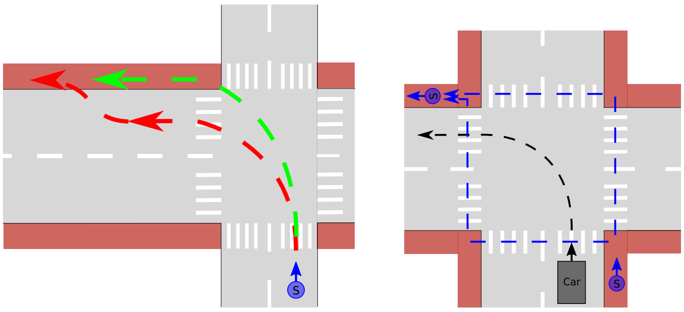
Preference Statements: Users were asked to rate their preference about different navigation conditions. The mean values were 2.67, 3.44 and 4.33 for MA, ARA and ART separately, see Fig. 6. By performing a one-way ANOVA, we found significant difference ($F_{2,24} = 8.244, p < 0.005$). Post-hoc comparisons showed that ARA is more preferred by the participants ($p = 0.043$) than MA. Users also preferred ART to MA ($p = 0.001$). However, there was no significant preference difference between ARA and ART ($p > 0.05$). The users were also asked to rate their preference of general audio feedback (combining their audio experience in MA and ARA) over tactile feedback. The mean values were 3.4 (audio) and 4.4 (tactile). By pairwise t-test, we found the participants significantly preferred the tactile over the audio feedback ($p = 0.040$). Comparing the interface preference, the mean values were 3.4 (2D Map) and 3.3 (AR). No significant interface preference was found ($p > 0.05$).

Discussion According to the results of the NASA-TLX rating and the preference, MA caused more subjective workload and was less preferred than AR group by users. From users' comments and our observation during the test, we found several reasons for that.

Environment Awareness: In condition MA, the environment was easily ignored when the user focused on the map interface, because it did not present real environment information. In the experiment, we observed that 2 participants violated traffic rules due to this reason, see Figure 7(a). Starting from a street without bicycle lane, they drove on the automobile lane. After a turning point at a junction, they looked at the map interface to check the route. In the meanwhile, they didn't notice there was a bicycle lane and still stayed on the automobile lane. After a while when they refocused on the driving, they realized the traffic violation and switched to the bicycle lane. On the contrary, in AR mode no traffic violation was observed, because users could see the real environment from the camera input and therefore always drove on the correct lane.

Timing of Notifications: When there were continuous short route segments, MA designed for car navigation delivered future navigation instructions in one notification to prevent missing turning points. For example, "in 50 meters turn left, then in 60 meters turn right, then immediately you reach your destination". It makes sense for car drivers but not for the Segway, because usually a car moves faster and needs more maneuver space than a Segway. Even for a Segway moving in the maximum speed (20 km/h), a distance of 50 meters still takes 9 seconds which means the Segway driver has more time to react than the car driver. To preload extra route information requires extra processing and memorizing for users and therefore increases the mental demanding. The correct timing of notification should always consider the current moving speed of the vehicle and the distance to the next turning point.

Orientation Update: The heading update in MA doesn't use orientation sensors, like a digital compass. The heading direction is calculated by the latest location updates. For example, when the user changes the orientation of the



(a) Environment awareness. (b) At a cross street.

Fig. 7. Left: The user lost environment awareness when focused on map interface. The red line denotes his/her actual trace. The green indicates the correct driving. Right: At the turning point of a cross street, the Segway has more degrees of freedom than a car, either along the edges or diagonal (if the bicycle way is not available).

Segway, the displayed map was not aligned to the new heading direction immediately, until a new location update arrived, which could be a delay of several seconds. Since MA is originally designed for the automobile navigation and cars can only move along the road, it is reasonable to update heading in such a way. However, it is different for Segway driving, because the Segway can move much more agile, e.g. rotating 180 degrees in place. In addition, there are more possibilities for the Segway driver at a turning point of a junction, i.e. going along the diagonal or edges, see Fig. 7(b). It is necessary to update the instant heading in the Segway navigation interface. In our user study, we found the heading update of MA was confusing to the users. This situation was even worse when there was strong ambient noise or relatively heavy traffic around, which was very normal at a junction of a main street. Due to these facts, the turning instruction played near the turning point was very likely to be missed partly. The user had to check the map for a correct turning directions. We observed that 5 users halted or slowed down to check the map in such situation, and then either went to a wrong direction or kept turning around hesitatingly. Unlike MA, in AR navigation interface the route forward direction was indicated by the 3D route and a turning instruction arrow, which pointed the way to the user directly in the real world. The users commented that it was intuitive and they can verify the forward direction by just one glance.

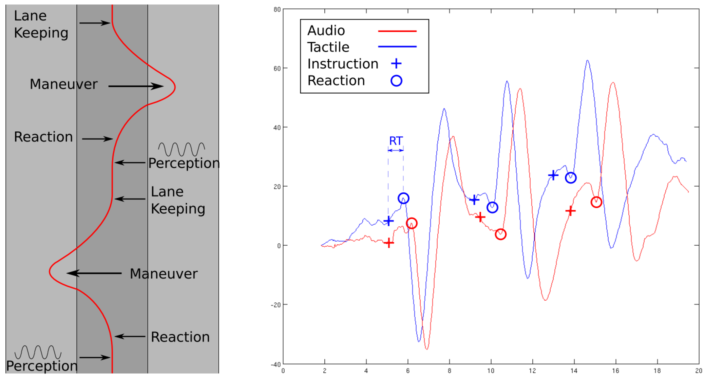
Vibro-tactile patterns: From the post-test results, using our vibro-tactile configuration, the tactile feedback was significantly clearer than audio feedback in real traffic environment and less affected by the environment. Before the user study, some users doubted the vibro-patterns would be hard to be distinguished from the Segway vibration due to the bumpy road. But after the test drive, they commented that although parts of the route was bumpy which caused vibrations of the handlebar, the vibro-tactile patterns' intensity was very different from that. They can perceive the signal clearly without any problem. The driving experience in ART was more relaxed, since users did not worry about missing instructions due to ambient noises. The encoding of the vibro-patterns were commented by users as well. Compared to an initial version of vibro-patterns, the current patterns were considered intuitive, as described in Sec. 3.2. The temporal-location encoding made the patterns easy to remember. In addition, two users expressed that the tactile feedback was more user friendly than the audio feedback. While they were waiting at the traffic lights with some pedestrians, a navigation instruction was played aloud. That attracted the passerby attention immediately, which was very embarrassing to the users. Moreover, because of strong sun light and screen reflection, sometimes the mobile display was hardly visible outdoors. In such case visual and auditory navigation aids were both affected by the environment, but users can still rely on the tactile feedback.

Although the tactile feedback was well accepted, we found a potential drawback of our current configuration. The designed vibration amplitude of the vibrator is limited [1], which means we better contact it with bare hands. If textile is used in between, the signal perception could become ambiguous. For example, in cold weather people usually wear gloves outdoors. The solution to such situation could be that we utilize a stronger motor or sew the motor inside gloves [18].

2D Map Preference: Although the 2D Map interface is more abstract and misses environment awareness, it can provide an overview of the area, from which users can preload upcoming turns and verify the route by checking the surrounding street network. In the AR interface, due to the perspective view, only the routes inside the viewing frustum were presented to users. The same issue was also found in previous works [12]. In our user study, some users commented that it was enough for them to know the next turning point. Preloading extra turning information was considered to be more mental demanding to them. While some other users, especially those who got used to the 2D Map interface of TVN, preferred to have more information for the route verification. This result was also reflected in the interface preference rating, see Fig. 6.

4.2 Study 2: Lane switching test in artificial environment

Design The second study is a Lane Switching Test (LST). The goal is to evaluate the impact of audio and tactile notification to the driving performance. LST is inspired by the Lane Change Test (LCT) [11], which evaluates the influence of the secondary task (e.g. visual, cognitive, etc.) to the primary task, car driving, in a controlled experiment. The influence is reflected by the driving performance, including sign perception, reaction, maneuver, and lane keeping. Since LCT is conducted in a simulator, the trace can be recorded and compared to an ideal maneuvering trace. The average deviation will be the performance indicator. However, since the ambient noise and the road condition could change the perception result from the indoor study, we want to measure the signal perception and users' reaction in the outdoor driving condition. Limited by the GPS accuracy and update rate, to trace a Segway movement sufficiently accurate in outdoor environment is not practical. Therefore we only measure the signal perception and reaction, which gives us the interval of reaction time. The primary



(a) Trace Sample (b) Data Sample

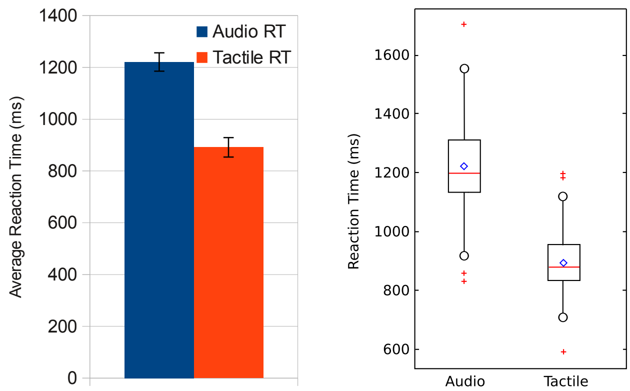
Fig. 8. Left: Segway trace example in LST. Right: A sample of gyroscope data in LST. Here we plot Audio and Tactile results together for comparison. The lane switching signal is marked by cross signs, which indicates the time point when the instruction is played. The time points of reaction are marked by circles. RT for Reaction Time.

task for a user is to drive the Segway, and the secondary task is to switch lanes when an instruction is perceived. If users can react faster in one condition, it means more space to maneuver in real traffic and less safety risk, e.g. assuming the Segway is moving in maximum speed 20km/h, every 100ms delay of reaction results in 0.6m further displacement.

We conduct the study on a long straight road (about 150m) of a parking lot. Three lanes, left, middle, and right are defined along this road. The within subjects design is used. Each participant needs to do this test under audio and tactile conditions separately. He/She starts from the middle lane at one end of the road and drives the Segway to the other end in the speed of about 15 to 20km/h. The experimenter sends switching signals to the iPhone mounted on the Segway via wireless connection. When the iPhone receives the signal, depending on the test mode, it either plays the audio instruction ("left" or "right" speech) or triggers the vibration (a pulse of 1 second length on the left or right grip) via a Wi-Fi connection (less than 10ms latency). When the participant receives a switching instruction, he/she has to switch to the corresponding lane and then returns back to the the middle lane immediately (to ensure that the participant does not know the upcoming instruction), see Fig. 8(a). No visual information is used in this test. We measure the driver's reaction time from the time point when the notification is played to the time point the handlebar is tilted (detected by the gyroscope of iPhone4). The data is collected by the mounted iPhone4, see Fig. 8(b).

Procedure and samples In the beginning, the experimenter (E) explained the procedure and demoed the correct maneuver. The participant (P) had several trials and then the real test started. Every P made 2 round trips using audio or tactile instruction respectively (the order was balanced). In each round trip E triggered 8 to 10 instructions depending on the Segway speed. Directions, left and right, were equally selected in a random order. 10 participants took part in this study: 2 females and 8 males, aged from 26 to 35, all students from the university.

Results In this study, all participants perceived and reacted to instructions correctly. The environment influence from the test location was very little. The mean reaction time were 1220.5ms and 891.2ms for Audio and Tactile respectively, see Fig. 9(a), 9(b). They were significantly different ($p < 0.0001$). The result indicated that by using tactile feedback instead of audio feedback Segway drivers can respond faster to instructions by 27% (in average 330ms faster). Assuming the Segway speed is 20km/h, 330ms delay corresponds to almost 2 meters further displacement.



(a) (b)

Fig. 9. Left: Average reaction time of audio and tactile feedback in LST (with 95% confidence interval). Right: Reaction time distribution. Mean values marked by blue diamond signs.

5 Conclusion

In the beginning of this study, we presented two hypotheses. We now review them in light of our results.

5.1 The utility of navigation interfaces

"Compared with the 2D-Map navigation interface in TVN, AR interface can reduce users' subjective workload."

Our user study demonstrated that participants experienced less cognitive workload in AR navigation interface (ARA and ART) than 2D Map navigation interface (MA). From our observation and users' comments, it was because MA was originally designed for in-vehicle navigation which was not suitable for the Segway. First, the driving of the Segway is different from the automobile: it is more agile than a car, and the maximum speed is limited to 20 km/h. Second, AR interface directly augments the environment with navigational instructions, which is intuitive to users. Third, the map interface detaches the user from the environment, which can result in safety risks. However, users' preference and comments indicated that the map interface can provide an overview of the route information and is helpful for preloading the upcoming turning points, especially for the users who are used to the 2D map based navigator. The design of the Segway navigation interface in the future should combine the features of map and AR modes, e.g. the screen displays the map interface when it is far from the next turning point, and replaces the interface by AR view when approaching the turning point. When designing a Segway navigation system, due to its unique features (agile movement and limited speed), the notification timing should take the current speed into account. While the heading update should utilize the orientation sensor.

5.2 The effectiveness of navigation instructions

"*The vibro-tactile turning instructions can be perceived by drivers clearly, and it improves their driving performance.* "

Indicated in the post-test results, users perceived vibro-tactile instruction very clear in real traffic. The tactile signal was robust to environment changes. The proposed vibro-patterns were intuitive to use and preferred by users. The driving performance was significantly improved when using tactile instructions than using auditory instructions.

5.3 Design implications and future research

Design vibro-patterns: In this study, we prototyped vibro-patterns for Segway navigation. It was demonstrated that the tactile feedback was superior to audio feedback for Segway drivers. Information encoded in vibration can be perceived faster, and is robust to the listening conditions. Therefore it has high potential to be used in other scenarios of the Segway. For example in noisy environment like airports, or higher temporally demanding tasks like security patrols or first aids.

In our study, to keep the mental demanding low we limited the number of patterns. Since the Segway is widely used in city touring, airport, security patrol, etc., various scenarios benefit from more information delivered to users than direction and distance, e.g. announcing Point Of Interest around the user. It would be worthwhile to investigate how such information can be encoded into a vibro-tactile patterns while keeping the complexity low. Or how other tactile displays can work for the Segway. One possible solution is to attach vibro-motors to the user's helmet and deliver directional information of POI, like the concept of the vibro waist belt [5].

Design AR navigation Interface: The current AR route visualization does not consider the object visibility in the scene, i.e. the route that should be occluded by a facade looks like being in front of the building. The occlusion is very important for the user to have the correct perception of depth, which makes the distance estimation easier and makes the AR layer more realistic. One possible direction is to render a 3D city model into the depth buffer as occluders. Furthermore, to improve environment awareness and reduce the violation to traffic rules, computer vision techniques could be used to detect lanes and highlight the correct lane on the AR display.

Design Segway user study: Since there was no on-road user study for Segway navigation before, we have some experience from the experiment to share. First, test areas and routes should be carefully selected. The test areas should have similar traffic pressure and the route complexity should be comparable to each other. Second, the driving security has the first priority. Some streets with heavy traffic should be avoided. During an experiment, the experimenter should follow the participant as an observer and also warn him/her about potential security risks (only if necessary). Third, if a participant has little experience with the Segway before, the tutorial has to be given thoroughly, covering different driving situations and including an on-road trial. Furthermore, since the on-road test depends on the weather condition, it is important to keep comparable weather conditions for all participants, e.g. temperature, wind, etc. In addition, the frequency of the user study is limited by the battery capacity of the Segway and other devices, which should be considered when scheduling experiments.

Alternative navigation display: The current mobile screen is hardly visible under strong sunlight. For AR perspective view, the pose of the display is also limited. The mobile mounting setup is fixed and does not adapt to the current pose of the Segway. To improve the viewability and comfort, other display modalities should be investigated. For example, a mobile laser projector can be used as an alternative display to project instructions (vector graphics) on the ground in front of the Segway.

Extension to bicycle: In this study we focused on the Segway use case. The current AR-Tactile navigation system can be deployed to a bicycle. Due to different driving experience, some adaptations should be implemented. For example, since the bicycle rider can hold the grips in different way, the design space should be explored, e.g. vibrators could be integrated into the helmet or the bicycle seat ([6, 7]).

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