# A Lab-Based Investigation of Reaction Time and Reading Performance using Different In-Vehicle Reading Interfaces during Self-Driving

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## ABSTRACT

The demand for autonomous vehicles (AVs) is rapidly growing these years. As AVs have a potential to free drivers' cognitive resources from driving to other tasks, reading is one of the common activities users conduct in travel multitasking. Nevertheless, ways to supporting reading in AVs have been little explored. To fill this gap, we explored the design of an in-vehicle reader on a windshield in AVs along three dimensions: dynamics, position, and text segmentation. We conducted two in-lab within-subject experiments to examine the eight kinds of in-car reading modalities that represented the combinations of the three dimensions in terms of drivers' reaction time and reading comprehension. Our results show a case where an adaptive positioning would be particularly beneficial for supporting reading in AVs. And our general suggestion is to use a static reading zone presented on-sky and in sentences because it leads to faster reaction and better reading comprehension.

## CCS CONCEPTS

• **Human-centered computing → Empirical studies in ubiquitous and mobile computing**.

## KEYWORDS

Automated driving, reading interface, safety, multitasking, comprehension, handover, windshield display, user study

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## 1 INTRODUCTION

No longer confined to the realms of science fiction, automated vehicles (AVs) are being produced by tech giants including Google/Waymo, Tesla, Apple, GM, and Toyota, and road-tested around the world. More and more non-driving related tasks/activities (NDRTs) can be performed in AVs while commuting, including watching movies, browsing news, and replying to emails [30, 46, 54]. Prior research on travel multitasking has indicated that reading, both for leisure and for business, is one of the activities that people are most likely to perform while traveling to maximize the value of their time [11, 34].

Before fully autonomous driving existed, drivers of *semi*-autonomous vehicles (i.e., Society of Automotive Engineers (SAE) levels 1-4 [25]) were required to stay vigilant in case they needed to take over the control of the vehicle. Specifically, with the help of Advanced Driver Assistance Systems (ADASs), drivers in SAE level 2 onwards were allowed to transfer the driving control to the system. And, when an ADAS encounters situations that it cannot handle safely, it returns full control to the human driver [10]. This transition process is called *handover* [65], and vehicles' human-machine interfaces (HMIs) should help drivers successfully handle it as quickly and safely as possible. In this research, we consider the scenario of SAE level 3 or 4, where drivers would be able to perform NDRTs during self-driving, and human override (handover) is still feasible.

Although reading in AVs seems appealing – especially during long trips, when people's propensity to engage in travel multitasking is likely to increase [40] – we argue that safety should not be compromised under any circumstances. Therefore, in-vehicle reading interfaces should be designed to ensure drivers' safety while still providing them with good reading experiences. However, precise ways of achieving this remain underexplored. To help fill that gap, this paper examines the potential benefits and challenges of engaging in reading on windshield displays (WSDs) [13, 19, 52], which

**Figure 1: The driving simulator with eye-tracker**

go beyond their immediate ancestor, the head-up display (HUD, e.g., [66]) by covering the entire windshield, and thus helping to keep drivers' attention focused at least partially on the road ahead. Assessing and comparing how different in-vehicle reading methods can provide a high-quality reading experience while compromising safety only minimally will help scholars and industry practitioners research and develop further enhancements to in-vehicle activities associated with windshields. Therefore, in this study, we explore three key design dimensions of on-windshield in-vehicle reading interfaces: their dynamics (static vs. adaptive), position (on-road vs. on-sky), and segmentation (paragraph vs. sentence). This results in a total of eight distinct reading modalities, which we investigated in terms of which ones led to 1) the best handover performance and 2) the best-quality reading experience, both subjectively and in terms of comprehension. To achieve this, we conducted two within-subjects laboratory experiments. In the first (N=25), we first examined drivers' handover performance and reading comprehension across the eight modalities. The second experiment (N=28) replicated the first, but with an added eye-tracking component, chiefly to help us obtain more insights into the reaction-time variations we observed.

This empirical research is, to the best of our knowledge, the first to explore the above-mentioned "reading-zone" dimensions of WSDs for automated vehicles in terms of both safety and the reading experience. In particular, this paper makes four main contributions to the literature:

- It shows that, when the reading zone was placed in a position dynamically overlapping the driver's view of the road, i.e., moving in response to prevailing road conditions, driver reaction times and reading comprehension were both better than when the reading zone was static – especially when whole paragraphs rather than individual sentences were presented.
- It demonstrates that, when reading zones were static, reducing the text in the reading zone to an appropriate length, i.e., a sentence, is much more important than having too much (paragraph type) or too little (RSVP type) text, in terms of both reaction time and reading-quality measures.
- It reveals that, when reading zones were static, placing them in an "on-sky" rather than an "on-road" position improved both reaction times and reading comprehension, despite eye-contact time increasing.
- It concludes that, in light of both safety and reading-comprehension considerations, a static, on-sky reading zone with sentence-by-sentence presentation is the ideal modality.

## 2 RELATED WORK

In this section, we review the relevant literature that informs the design and analysis of our project. Our work is based on previous research on multitasking in automated vehicles and reading.

### 2.1 Multitasking in Vehicles

Multitasking is an active research area in ubiquitous computing, but scholars' definitions of it vary [29]. Among the many subcategories of multitasking, travel multitasking – such as passengers deliberately engaging in productive activities (e.g., working, studying) during their commutes – is usually considered to increase the value of time (e.g., [11, 34, 45]) because distractions during commuting via public transportation are lower than in many other day-to-day situations [34], which mitigate the risks that distraction and inattention could seriously weaken driver performance and threaten road safety [44, 50, 51]. This led us to intuit that drivers' demand for performing NDRTs during their commutes will increase alongside the market penetration of AVs [8, 30, 46, 54]. During automated drives at SAE level 3 [25], AVs can independently deal with many situations, but timely driver responses to these vehicles' handover requests remain vital to avoiding accidents [70]. Various studies addressing this problem have been conducted, but so far, they have treated NDRTs mainly as a distraction [15, 28, 37, 49], rather than an opportunity for productivity.

Since the invention of the automobile, drivers have had to share their limited cognitive resources for performing *concurrent multitasking* [58], i.e., simultaneously executing a primary task (driving) and secondary tasks (such as interacting with an in-car entertainment (music/radio/CD player) system) [51]; and there has been a performance trade-off (i.e., dual-task interference) when the available cognitive resources are insufficient [68, 69]. When visual distractions loads with cognitive tasks (e.g., adding double-digit numbers), it may cause reduced alertness [20] and longer reaction time [63]. Given that interruptions caused by handovers are both urgent and unpredictable, the times drivers take to react to them are vital to safety. In this context, smooth attention switching during autonomous driving requires alertness, but maintaining a sufficient alertness level in AV drivers remains a challenging problem. As task distractions and task resumption become central concerns, immersive environments should include structured transitions designed to optimize drivers' responses to potential hazards [38].

The contextual uniqueness of multitasking in one's personal vehicle implies that secondary-task demand could affect drivers' workload [39, 68, 69] and thereby impact driver interruptibility. To maintain drivers' alertness and increase their situational awareness, prior researchers have studied a variety of methods, including placing vehicle information on the windshield (e.g., HUDs [3, 60]) and leveraging other senses (e.g., sound, light, vibration, etc. [21, 27, 31, 72]).

Some have studied NDRTs during automated driving and measured performance when handover requests were triggered. Schartmüller et al. [59], for instance, assessed both typing effort and driving performance in handover situations. They mounted a keyboard on the steering wheel, and aimed to provide an exemplary safe and productive working environment. However, that paper focused narrowly on typing tasks, without reference to their reading component (if any) or other reading activity. We acknowledge that reading a real book is a relatively dangerous behavior for vehicle drivers because it keeps their gaze off the road, which in turn may jeopardize handover ability. Hence, an in-vehicle reading interface should be used if a balance is to be struck between reading performance and driving safety. Riegler et al. [53] studied performing reading tasks on WSDs during autonomous driving. However, they only addressed sentence-by-sentence reading and static vs. dynamic reading zones, without reference to on-road vs. on-sky reading-zone placement, among other potentially relevant factors.

Nevertheless, despite the rich work on multitasking in AVs, little research has explored supporting reading, one of the most common activities of multitasking during travel, in AVs. To the best of our knowledge, this is the first empirical research that explores different combinations of positioning and presentation of reading zones on the WSD in AVs, and our findings not only indicate an ideal combination but explain how the specific combination would be more or less suited for being presented on the WSD in AVs.

## 2.2 Reading in Vehicles

Using WSDs as the reading interface is promising, as such displays allow users to engage in highly-automated driving and performing NDRTs [18]. Meanwhile, since reading was a primary task in our study, we took account of the large body of literature on how distractions affect reading. Navalpakkam et al. [43], for example, showed that readers took longer to comprehend what they were reading if their reading conditions were highly distracting. Also, readers may have unpleasant reading experiences when they are distracted; constant interruptions can lead to feelings of pressure and frustration [35].

Among several measurements of reading performance, comprehension reflects how well readers understand the materials they read, as it represents "*the full sum of the cognitive, perceptual, and affective processes that prepare readers to apprehend, grasp, and assimilate the essence of what is read*" [71]. Johnston et al. [26] noted that the most common way to assess participants' level of comprehension is through comprehension questions specially tailored to the material they have read. In our study, we use comprehension as a measure to evaluate the comprehension scores of reading materials.

When information was present in a certain area (i.e., the functional field of view), drivers could catch it without moving their head or shifting their eyes away [7]. Hence, limiting the text to a certain reading area on the WSD might help drivers maintain their alertness toward the road and be able to read text from it; in this case, the ways of presenting the reading area should also be addressed to obtain efficient reading and maintain alertness. Previous research by Rzayev et al. [56] examined how text presentation, position, and orientation affected reading in virtual reality (VR). The same study compared two presentation types, rapid serial visual presentation (RSVP) [12] and paragraphs, and found that RSVP was a promising option for reading short texts on the move in VR, but that paragraph presentation was more suitable when reading without moving was the primary task. Not focused on articles but notifications, Hsieh et al. [24] studied presentation styles for showing message notifications in VR. They found fixing the notification zone at a specific place has the advantage of being an anchor that makes it easier to find the notification, but propose a context-aware presentation approach because an ideal presentation style would depend on the present activity the user is undertaking.

In summary, previous work suggests that reading in AVs is possible and desirable. However, drivers should also pay attention to road conditions, which may overlap with reading zones – a dilemma that remains underexplored. Although Grout et al. [17] showed that users could complete traditional reading tasks in a virtual environment with near-equivalent performance to what they attained in the real world, the effect of text presentation on WSDs has not yet been studied. Our experiments, therefore, measured not only comprehension levels, but also the effects of various WSD reading modalities.

# 3 STUDY ONE: DESIGN CHOICES BETWEEN DYNAMICS, POSITION, AND TEXT SEGMENTATION

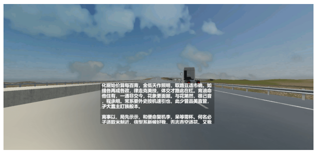
To study how the three key dimensions of a reading zone – dynamics, position, and text segmentation – affect drivers' reaction time and reading quality, we conducted a 2×2×2 within-subjects experiment, examining a total of eight reading modalities (as shown in Figure 2). The research questions of the experiment are as follows (RQs):

- **RQ1:** Which of the eight reading modalities yield the fastest reaction times?
- **RQ2:** Which of the eight reading modalities produce the best a) reading comprehension and b) subjective reading experience?

Before proceeding to the main experiment, we conducted a preliminary one to explore various types of text segmentation; and its results guided our final decision to generate two variations of text segmentation and two positions.

## 3.1 Preliminary Experiment

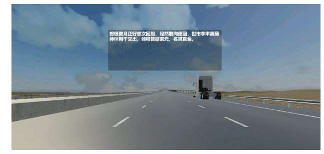
The preliminary experiment, conducted with 41 participants, initially presented the reading zone on-road, and applied two dynamics, Static and Adaptive, to three kinds of text segmentation: paragraphs, sentences, and RSVP. We included RSVP because, on the one hand, it has been found to enhance reading speed and readability in mobile environments [4, 5]; and on the other, because it may increase cognitive load and reduce comfort as the length of a passage increases [1, 6, 12, 36, 55]. We observed early in this preliminary investigation that having an adaptive reading zone decreased the participants' comprehension, but was linked to shorter reaction times; and that the RSVP approach negatively affected the participants' cognitive performance, presumably because of increases to cognitive load. We also noted that smaller segments of text, i.e., sentences and RSVP, allowed the participants to track and read text more clearly than longer ones (i.e., paragraphs) did, because the latter overlapped more with their view of the road. Consequently,



**(a) Stc - Road - Para**

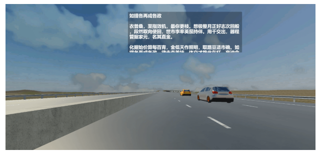
**(b) Stc - Sky - Para**

**(c) Stc - Road - Sen**

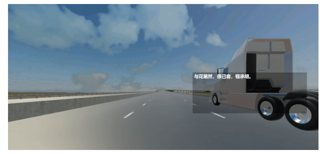


**(d) Stc - Sky - Sen**

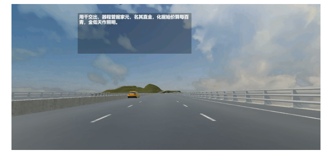
**(e) Adap - Road - Para**



**(f) Adap - Sky - Para**



**(g) Adap - Road - Sen**



**(h) Adap - Sky - Sen**

**Figure 2: Simulated scenes representing all eight reading modalities in the experiment. The reading zone with adaptive movement dynamically moves with a nearby vehicle, if any; otherwise, it stays in its current position, as in static mode**

in later phases of the preliminary study, we also examined placing the reading zone in an on-sky position – specifically, overlapping with the sky – and found that this resolved the earlier problem with paragraph segmentation. Based on these results, we decided to not include RSVP mode, but to add position as a third dimension, in our main experiments.

## 3.2 Study 1 Design

*3.2.1 The Three Dimensions.* It seems intuitive to allow WSDs to present as much text as possible. However, doing so will tend to result in a large reading area that blocks drivers' view of the road. On the other hand, as our preliminary study showed, the RSVP approach could potentially increase the driver's cognitive load and impair reading comprehension, presumably due to the loss of context, increasing the difficulty of reading. For this reason, limiting the displayed text to an appropriate region, i.e., a *reading zone*, is a better choice for reading tasks during driving, as it theoretically allows drivers to shift attention to the road at any time. Each of the above-mentioned three dimensions that we considered in regard to presenting text in a reading zone is discussed in turn below.

**(1) Dynamics: Static (Stc) vs. Adaptive (Adap).** Dynamically attaching a reading zone to a vehicle's ADAS [61] and collision-avoidance system (CAS) [42]) should be possible using machine-learning techniques, given that such techniques have successfully been used to detect and avoid accidents [2, 41]. Thus, the first comparison we made was between a static position – i.e., the reading zone is fixed at a specific location on the WSD – and an adaptive one: i.e., the reading zone constantly moves with a nearby vehicle on the WSD; it remains fixed when no nearby vehicle is detected. Riegler et al. [53] used a similar technique of intelligently positioning content on a WSD, and found that reading performance was better in the dynamic state than in the static one, a finding well aligned with those of our preliminary study. On the other hand, based on our observations that long paragraphs of text can fill the reading zone and thus potentially block the road scene, the second dimension, *position* of the reading zone, was introduced.

**(2) Position: On-road (Road) vs. On-sky (Sky).** Since potential dangers to drivers arise almost exclusively on the road ahead, it seems plausible that placing the reading zone on-road will better ensure safety than placing it anywhere else. On the other hand, doing so entails overlaps between the reading zone and vehicles in front, which is likely to harm readability [32]. Participants in our pilot experiment also reported that, as the length of a reading text increased, its readability decreased, as well as negatively impacting their view of the road. We, therefore, assumed that an on-sky reading zone, specifically *on* the sky above the road, might mitigate these issues. In our experiment, the vertical distance of the reading zone between on-sky and on-road is 450 pixels in the simulator.

**(3) Text Segmentation: Paragraph Type (Para) vs. Sentence Type (Sen).** In addition to dynamics and position, we considered that how texts are segmented might also matter. Whereas a lengthy text segment may occlude drivers' sight, a too-short one, as we observed with RSVP in our preliminary study, can increase cognitive load. Thus, we included two types of text segmentation: paragraphs and sentences. Specifically, *paragraph* segmentation displayed an article in paragraphs within a scrollable reading zone, and *sentence* segmentation displayed only one sentence at a time within a switchable reading zone. We split paragraphs into sentences using final punctuation. However, if a sentence is too long to present in the reading zone without scrolling, it would be further split by the semicolons, if any. The chapters we selected in our study can therefore present the entire sentence within the reading zone in this way. Thus, this type of presentation greatly reduced the amount of text in the reading zone.

*3.2.2 Reading Tasks.* To measure reading comprehension, we asked each participant to read a book chapter 600-800 characters in length via the reading zone on a virtual WSD, and use buttons on the steering wheel to control the text. In order to keep the difficulty of reading unaffected and let reading material unpredictable (avoid having seen or familiar with it), the chapters we chose come from a well-known but relatively low-difficulty book - *One Hundred Thousand Whys, Traditional Chinese Edition* [23], the target readership for which was originally considered as children, and which is widely seen as high-quality literature [67]. As suggested by [64], the reading speed of native Chinese speakers can reach an average of 255 characters per minute, we balanced the length of each selected chapter ($M$ = 733.8 characters, $SD$ = 63.3) such that participants would have enough time to read at least 500 characters


**Figure 3: Notification of handover. This scene will appear when the handover request is triggered, and, at the same time, the reading zone will be cleared from the WSD**

(in 120 seconds) within the space of one driving task, and it is the sufficient length to get answers to the comprehension test. During the experiments, we ask participants to immerse themselves in the reading task while keep themselves safe during driving.

*3.2.3 Driving Tasks.* The driving tasks were designed to simulate the experience of autonomous driving in an AV sedan for 130 seconds, with the participant portraying the driver. The scenes were built using a Unity engine and consisted of a three-lane highway in a rural setting, with the vehicle moving at a constant speed of 65 miles per hour (the standard driving speed on Taiwan's highways). On this road, light traffic consisting of non-participant-operated trucks and sedans could be seen. We designed two different handover scenarios, both based on scenario 9: Danger zone/obstacle ahead (detected by on-board sensors) in Gold et al. [16]. The handover scenarios were implemented in the above-mentioned highway terrain, and consisted of a truck and sedan overturning at a designated accident point.

Once the simulator detects such an incident, it triggers a *handover request* to warn the driver to avoid a collision. Although in reality the time available for handovers is affected by the range of the system's sensors and their ability to predict system boundaries, for simplicity, we set the maximal handover time at 3 seconds, meaning that if there is no handover within 3 seconds of a handover request, the participant will crash into the obstacle on the simulator. Autonomous driving is deactivated once the handover request is triggered, and the driver should manually perform a "sufficient" handover to avoid the crash, defined as a 2-degree change of the steering wheel angle or a 5% change in brake/accelerator-pedal actuation (as recommended by [70]).

We instructed the participants that they should drive as they would normally, avoiding collisions. In all driving scenarios, the obstacle on the road (in the form of damaged vehicles) took place at the 120th second, and the participants were expected to avoid collision with it by stepping on the brake or turning the steering wheel. When the "accident" happened, the simulator triggered a handover request, consisting of an acoustic warning, the WSD flashing in red, and the text "Handover" displayed in the center of the screen for 0.3 seconds [37, 72]. (Figure 3).

*3.2.4 Equipment.* The road scenes and handover scenarios built with a Unity engine were presented to the participants in fullscreen/borderless mode on a 49-inch 32:9 Curved UltraWide IPS Monitor. The fully textured graphics were generated by PC hardware that delivered a 60Hz frame rate at 3840 × 1200 resolution. We simulated a WSD on the monitor, and presented all reading zones as white text (28px) on a translucent gray background (700px × 250px). We controlled the size of the reading zone in order to offer consistent reading experience. The participant's "vehicle" was controlled using a Logitech G29 Steering Wheel Set with pedals and clutch.

*3.2.5 Data Collection.* Each participant performed eight driving tasks, referred to as rounds. In each round, we collected safety-related and reading-comprehension measures. The former comprised reaction time, defined as the time that elapsed between the start of a handover alert and the system's detection of the completion of a sufficient handover. We measured reading comprehension using a simplified version of the seven-item scale developed by Dyson et al. [9]. In our study, we used four of these multiple-choice items, covering *Main idea*, *Main factual*, *Recognition*, and *Incidental*. Each item includes four answer options: one correct, two wrong, and the last one "*I don't know*." The correct answer to each question was deemed to be worth 25 points, and thus a participant's score would be 0, 25, 50, 75, or 100. As we proceeded from an assumption that in-car reading should prioritize safety first and reading comprehension second, our evaluation of the measures focused on lowering reaction time; i.e., reading comprehension was evaluated on the premise that reaction time should be short enough for the driver to avoid a collision. At the end of the experiment, they were asked to complete a general preference questionnaire, in which they selected their top three favorite reading modalities with regard to safety, and their top three with regard to reading comprehension. The qualitative results were presented and discussed together with Study 2 in Section 5.

## 3.3 Study 1 Procedure

Upon arrival, the participants were first asked to make themselves comfortable in the driver's seat, with their feet easily reaching the pedals and their hands correctly positioned on the steering wheel. Participants warmed up first by practicing driving in the same scenario (not including other vehicles crashing), with no time limit. The moderator then explained the reading modalities' three dimensions. The order of the eight rounds was counterbalanced to compensate for learning effects; and the eight different book chapters were randomly assigned to the eight reading modalities.

As part of their familiarization with the simulator, participants could practice using the control buttons to scroll/switch text, and experience a handover request similar to the one they would face in the actual round. After they considered themselves prepared, they started the eight-rounds experiment. In it, the participants did not need to perform any driving tasks before the handover request was triggered, since autonomous driving was active from the beginning of each round. They were also notified of which reading modality they would be using before entering each round. The stages of each round and the post-round questionnaire are illustrated in Figure 4. At the end of each round, the participants completed the four-item comprehension questionnaire described above. We then provide a general preference questionnaire and conducted a brief interview with each one, asking for his/her thoughts about each modality and further ideas for performing in-vehicle activities in AVs.

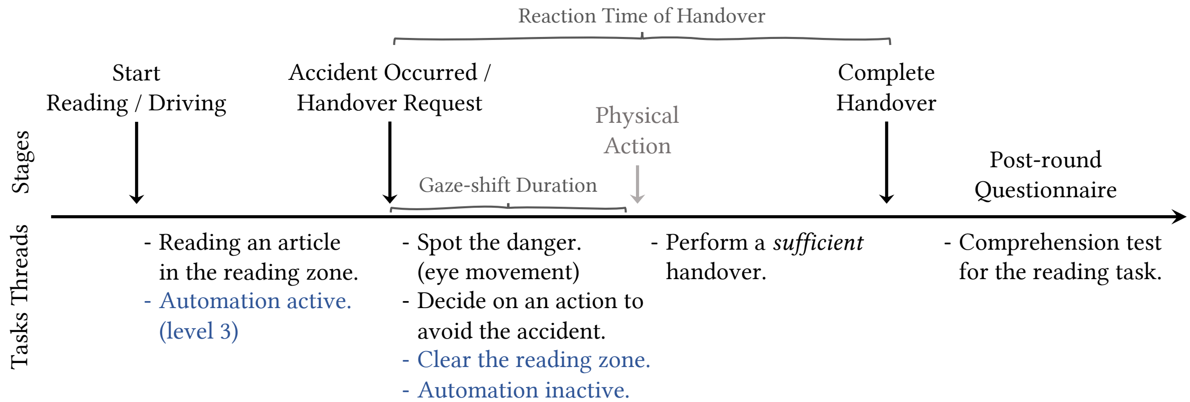



**Figure 4: Timeline of stages and task threads associated with each stage. The driver/participant performs the tasks marked in black, and the simulator performs those marked in blue. *Gaze-shift duration*, used only in Study 2, was recorded with an eye-tracking system**

## 3.4 Study 1 Participants

Via Facebook groups intended for connecting researchers with research participants in Taiwan, we recruited 25 Taiwanese individuals ($M$ = 32.1 years old, $SD$ = 6.1); ten identified as female and 15 as male. All had held valid driving licenses for two years or more and had normal or corrected-to-normal vision. All had some higher education: five (20%) were studying for or had finished a bachelor's degree, 15 (60%) were studying for or had finished a master's degree; and five (20%) were studying for or had finished a Ph.D. Seven (28%) were enrolled as students at the time of the study, and 18 (72%) were not. All the participants self-reported having a habit of travel multitasking when commuting to and from work/school, including reading news, domain-related articles, and social-media posts, and doing this would not make them feel motion sickness. Four participants (16%) reported reading one to two hours per day, 15 (60%) between two and four hours per day, and six (24%), more than four hours per day. All were regular drivers: six (24%) drove two to three days per week; 15 (60%), four to five days per week; and four (16%), more than five days per week. The participants were compensated with approximately US$15 for their time.

## 3.5 Study 1 Results

Our main results are depicted in Figures 5, 6. Two participants were excluded due to system errors. Linear mixed-effect regression was used to explain the variation in reaction times and comprehension scores, with *Adap-Road-Para* used as the reference level in the model. We found not only main effects but also interaction effects among the dimensions, which will also be discussed below.

*3.5.1 RQ1.* A shorter reaction time indicates greater safety. The reaction-time results, as shown in Figure 5, indicate that reading zones using adaptive positioning ($M$ = 0.90 sec, $SD$ = 0.34) were associated with shorter average reaction times than those using static positioning ($M$ = 1.10 sec, $SD$ = 0.52, $t(153)$ = 5.17, $p < .001$). The reaction-time/safety benefit of using adaptive positioning was particularly obvious for reading zones that presented paragraphs on-road. That is, static reading zones presented in paragraphs, regardless of whether they were positioned on-road or on-sky, led to much longer reaction times ($M$ = 1.29 sec, $SD$ = 0.58) than those presented in sentences ($M$ = 0.91 sec, $SD$ = 0.38, $t(153)$ = -2.60, $p$ = .01); but this difference was not observed when the reading zone used adaptive positioning. This suggests that presenting the reading zone dynamically particularly helped safety when presentation of the reading material was by paragraphs. This was likely because task-resumption time for reading paragraph is longer, and thus, dynamically positioning the reading zone closer to the road scene helped reduce the time for switching between reading and driving. On the other hand, we did not observe a marked difference in reaction time between Adap-Sky ($M$ = 0.90 sec, $SD$ = 0.39) and Stc-Sky ($M$ = 1.01 sec, $SD$ = 0.54). This tends to confirm our previous observation that the safety advantage of adaptive mode over static mode may be particular to the on-road placement of the reading zone.

On the other hand, when the reading zone was positioned statically, the participants' reaction times were shorter when it was on-sky ($M$ = 1.01 sec, $SD$ = 0.54) than when it was on-road ($M$ = 1.19 sec, $SD$ = 0.49, $t(153)$ = -2.66, $p$ = .01). In particular, the **Stc-Road-Para** combination yielded an especially long reaction time ($M$ = 1.43 sec, $SD$ = 0.52). In addition, static reading zones that presented sentences ($M$ = 0.91 sec, $SD$ = 0.38) tended to be associated with shorter reaction times than those that presented paragraphs ($M$ = 1.29 sec, $SD$ = 0.58, $t(153)$ = -2.60, $p$ = .01). Consequently, because it combined on-sky positioning and sentence-by-sentence presentation, the Stc-Sky-Sen combination was linked to the shortest reaction times ($M$ = 0.86 sec, $SD$ = 0.43).

Finally, while Figure 5 appears to show shorter reaction times for reading zones that presented reading material in sentences rather than in paragraphs, we did not actually identify a main effect of such segmentation. This could have been due to the relatively small size of our sample.

*3.5.2 RQ2.* In terms of reading comprehension, the participants had significantly higher comprehension scores when the reading zone used the combinations Sky-Sen ($M$ = 80.43, $SD$ = 19.66, $t(161)$=3.35, $p$ = .001) and Sky-Static ($M$ = 77.17, $SD$ = 24.05, $t(161)$=3.45, $p < .001$). That is, when the reading zone was placed on-sky, the

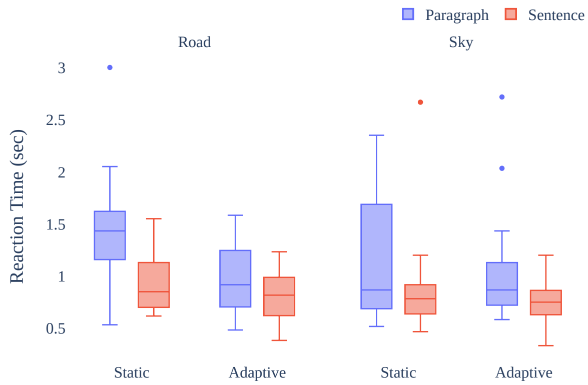



**Figure 5: Study 1 results: Handover Reaction Times**

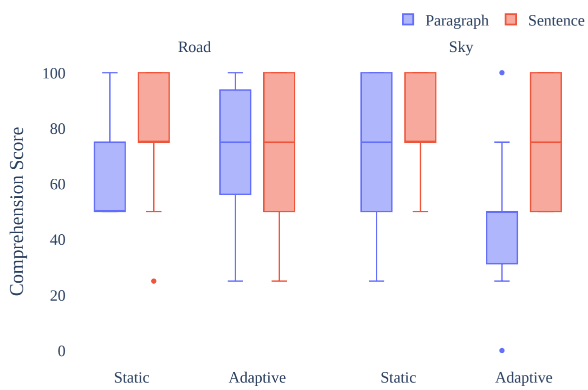



**Figure 6: Study 1 results: Reading-comprehension Scores**

participants' comprehension was significantly higher if the text was presented statically and in sentences – a finding consistent with the shorter reaction times mentioned earlier. Their comprehension was particularly weak, however, when the reading zone was adaptive ($M$ = 63.04, $SD$ = 25.68), and especially poor when presentation was by paragraphs ($M$ = 48.91, $SD$ = 21.95), as seen in Figure 6. This suggests that dynamically moving the reading zone around the sky harms reading comprehension. Yet, when the reading zone was on-road, dynamically moving it seemed to help participants process the paragraphs. That is, their comprehension was lower for Sta-Road ($M$ = 66.30, $SD$ = 19.38) than for Adap-Road ($M$ = 72.83, $SD$ = 22.50). This implies that, in addition to helping shorten the reaction times associated with on-road reading zones presented in paragraphs, adaptive positioning also helped participants comprehend such paragraphs. From this, we can conclude that the adaptive approach is only beneficial when the reading zone is on-road.

### 3.6 Study 1 Discussion

To sum up, when examining the eight reading modalities in terms of the participants' reaction times and comprehension scores, we found the following. 1) Adaptive mode benefited reaction times and comprehension when reading zones were placed on-road and presented in paragraphs, but harmed comprehension and did not shorten reaction times when they were placed on-sky. Indeed, when the reading zone was on-sky, presenting it adaptively yielded the lowest comprehension scores. 2) When reading zones were presented statically, an on-sky position was associated with shorter reaction times and better comprehension than an on-road position was; and sentence-by-sentence presentation was associated with shorter reaction times than paragraph presentation was. 3) Whenever reading material was broken down into sentences rather than paragraphs, presenting it on-sky led to shorter reaction times than presenting it on-road did. Bringing these characteristics together, and with the aim of facilitating both short reaction times and high reading comprehension, it seems that **Stc-Sky-Sen**, i.e., statically presenting the reading zone in sentences *on* the sky, was the optimal modality out of the eight that we examined.

On the other hand, our finding that presenting reading zones statically in the sky generally led to shorter reaction times prompted us to dig deeper for a reason. That is, although on-road positioning can cause overlapping issues, an on-sky position implies a greater visual distance between the reading zone and the road ahead. Thus, we replicated our experiment, but adding eye-tracking information to improve our understanding of this counterintuitive phenomenon.

## 4 STUDY TWO: EYE-MOVEMENT ANALYSIS

The specific purpose of our second study was to leverage eye-movement data to further compare gaze-shift duration between on-sky and on-road reading zones. Thus, we developed a third research question, as follows:

- **RQ3:** Does an on-sky placement of the reading zone lead to longer gaze-shift duration with the reading material following a handover request, as compared to an on-road placement?

### 4.1 Study 2 Design & Procedure

*4.1.1 Gaze-shift Duration.* Gaze-shift duration is the duration between the start of a handover request and when the "driver's" sight shifts to the obstacle object, as depicted in Figure 4. We choose 200 ms fixation of eye-contact as the duration threshold, in line with previous research [14, 47, 48, 57]. Under this standard, a relative gaze stationarity greater than or equal to 200 ms is considered a fixation. In Study 2, the gaze point was deemed to be on the obstacle if it fell within an area 180 pixels from the obstacle (Figure 7). Eye-contact with the obstacle was held to be valid if it had a fixation duration within that area for at least 200 ms.

*4.1.2 Procedure.* The only change to the procedure, as compared to Study 1, was the addition of an eye-tracker calibration procedure. We mounted a Tobii Eye Tracker on the bottom of the monitor (see Figure 1), and integrated it with the simulator in the Unity engine to enable us to collect the participants' eye-movement data.

For Study 2, 28 participants (12 females) – none of whom had taken part in Study 1 – were recruited using the same method as for Study 1. Their average age was $M$ = 30.0 ($SD$ = 6.5). Likewise, all were Taiwanese and 35.7% were students. Most were frequent readers (85.7% read at least two hours per day) and frequent drivers (67.8% drove at least four days per week), and self-reported habitually engaging in the same travel-multitasking behaviors as the Study 1 participants.

**Figure 7: An example eye-movement trace trajectory. The elapsed time between the start of a handover request and when the driver's sight shifted to the obstacle object is termed *gaze-shift duration*; the red-marked area is for distinguishing whether the gaze point was on the obstacle.**

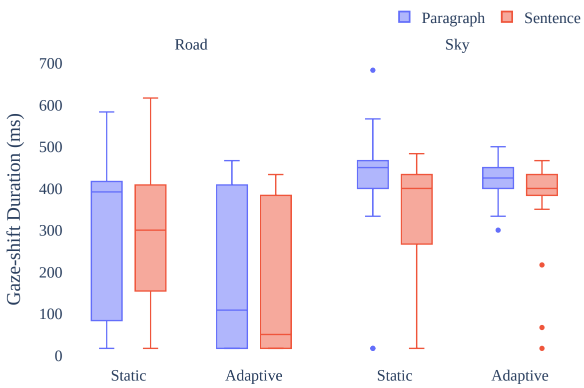



**Figure 8: Study 2 results: Gaze-shift Durations**

## 4.2 Study 2 Results

The non-eye-tracking results of Study 2, regarding reaction times and reading comprehension, were similar to those of Study 1. Two participants were excluded due to system errors, and the gaze-shift duration longer than 1 second were regarded as invalid records and outliers and were removed from the results. We again used linear mixed-effects regression in our analysis, and adopted *Adap-Road-Para* as the reference level.

*4.2.1 RQ3.* As seen in Figure 8, on-sky placement of the reading zone ($M$ = 387.28 ms, $SD$ = 122.58) led to significantly longer eye-contact time than an on-road placement did ($M$ = 238.02 ms, $SD$ = 192.96, $t(164.55) = 4.80$, $p < .001$). It is also worth noting that an adaptive reading zone presented on-road was associated with the shortest gaze-shift duration ($M$ = 182.99 ms, $SD$ = 184.45). This result was expected, as an adaptive on-road reading zone is not obscuring nearby vehicles or road scenes, but is attached to them, allowing drivers to be aware of potential obstacles ahead.

## 4.3 Study 2 Discussion

From Study 2's results, it is clear that placing the reading zone on-road helped shorten gaze-shift duration, as compared to an on-sky placement. However, the fact that on-road placement did not also decrease reaction time, but rather lengthened it, suggests the phenomenon of *seeing but not perceiving*. That is, when attending to reading text in a reading zone on-road, despite the short visual distance between participants' reading focal point and the view of road ahead, they were less likely to perceive accidents when they took place. According to the participants and our own observations, this was because text/vehicle overlap made it harder to detect changes in the road scene. Placing the reading zone statically in an on-sky position, on the other hand, allowed them to perceive changes on the road ahead clearly, likely because obstacles fell within their peripheral vision, which is well-known to be used for encoding a dynamically changing visual environment and detecting motion [62]. These results suggest that despite it resulting in longer gaze-shift duration, placing a static reading-zone on-sky could avoid the overlapping issue and take advantage of the characteristics of human peripheral vision.

# 5 QUALITATIVE RESULTS

As mentioned earlier, we conducted a brief post-study questionnaire and interview with all study participants, with the goal of gathering data on their thoughts about in-vehicle reading and smooth handovers. In this section, we present participants' self-reported preference for the reading interface and their feedback from the interview.

## 5.1 Interview

We transcribed all interview recordings and subjected them to a simplified version of qualitative coding with affinity diagramming [33] with a bottom-up process. The key themes that emerged through iterative grouping and labeling were 1) performing in-vehicle reading, 2) reading on the windshield, and 3) ways of switching attention.

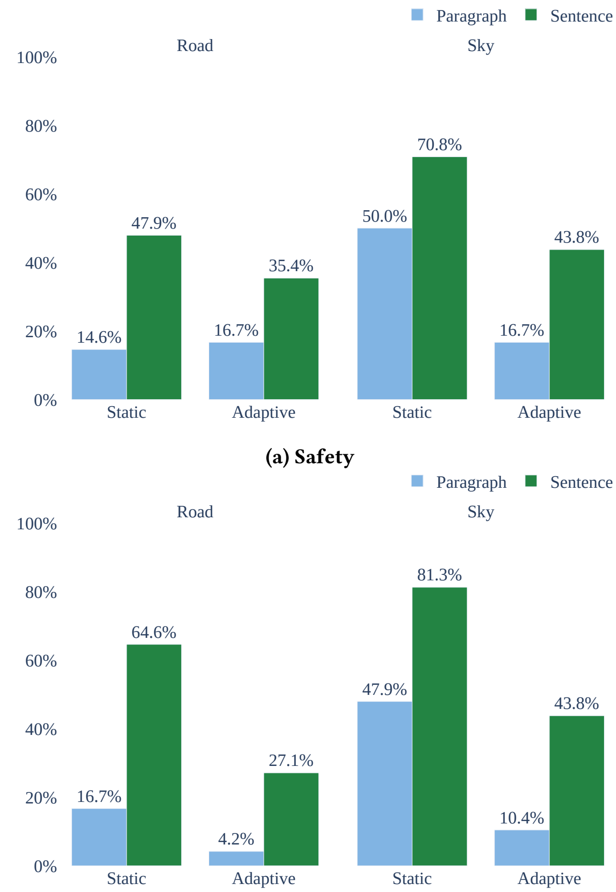
*5.1.1 Safety Aspects.* When we asked the interviewees how they liked performing reading tasks during autonomous driving, many noted that they were unfamiliar with AVs, and that they were therefore still accustomed to observing road conditions while driving to gain a sense of safety. As P46 explained, "*Since we were still used to watching the road conditions, it seems better that the words not block your vision when you are driving. I still don't fully believe in self-driving cars.*" Some agreed that adaptive movement helped maintain their alertness, and thus made them feel safer: "*In terms of safety, placing reading zone adaptively to the vehicle and at on-road region is the safest, but an uncomfortable experience, as you will feel nervous, as if the car is about to crash*" (P25). However, some expressed a countervailing view that the Adap-Road reading modality actually reduced their sense of safety, because it would block their view: "*The adaptive mode freaks me out because I would know cars are moving nearby, so it interferes with me when I'm driving*" (P17). The same participant provided the following further reason: "*I don't like the adaptive mode because it would block my sight while driving, which put me under a lot of pressure*". Moreover, various participants (P06, P11, P25) proposed alternatives to Adap-Road. P06, for instance, told us: "*I would suggest not letting the text overlap with the vehicle, because text in the on-road region will occlude the road conditions, whereas in the on-sky region, this is relatively unlikely*".

*5.1.2 Reading Aspects.* Several participants mentioned their text-form preferences for reading on the WSD. As P11 put it, "*I think the* *sentence type was better than the paragraph type because it is easier to be interrupted. After reading a sentence, I can first look at the road conditions and then look at the next sentence.*" Also, because "*[h]aving less context in sentence-type presentation takes some effort to recall while reading*" (P19), two interviewees (P19, P40) also suggested that a button be added so that drivers could switch between sentence and paragraph presentation whenever they wanted to. Moreover, some participants were concerned that when using WSDs, light effects could reduce reading performance. For example, P51 mentioned that strong light would make it hard for drivers to read text: "*When driving on the highway, it is very common for drivers to face backlit conditions. In such circumstances, it would be too hard for us to read the passages*" (P51). Shifts of visual attention were another frequently mentioned concern; both P09 and P41 noted that focal length might affect reading comfort. As P41 put it, "*If there is a car nearby and you project a reading section onto your windshield, the focus of your eyes will change from near to far. That is, it will be a little uncomfortable for the switching time, and you also have to understand what is happening at the moment*".

*5.1.3 Switching Attention.* We also asked the interviewees about how to address emergency conditions that arose during autonomous driving. They tended to rely on an acoustic method, the alarm sounding. Some would have preferred the driving system to tell them the reason for each warning and what they needed to pay attention to. As P40 noted, "*The vehicles should distinguish the nature of the emergency situation and use the alarm buzzer to explain it to the driver*". However, some other interviewees disagreed that acoustic alerts were helpful: "*If I am listening to music, I might not differentiate between its sounds and the alarm, and therefore might not be aware of accidents*" (P25). Several also suggested that vibration, perhaps via the steering wheel (P29), might be an ideal means of redirecting their attention to emergency situations. P25 also commented that "*I might be shocked by the vibration when the emergency comes in because sometime I would feel sleepy while driving*".

## 5.2 User Experience

Finally, participants voted for their favorite top three reading modalities; we asked them to vote based on their sense of safety and reading experience. Figure 9 shows the frequency of each modality being placed in the top three list. Consistent with the quantitative result, Stc-Sky-Sen is the most often considered the most favorite modality in terms of both safety and reading experience. The second most-often one is Stc-Sky-Para for safety and Stc-Road-Sen for the reading experience, respectively. We note that participants generally more often preferred the reading zone presented in sentences than in paragraphs, in terms of both safety and reading experience, and they also more often preferred static positioning than adaptive positioning. The combinations of adaptive positioning with paragraph segmentation were the two the least often chosen for the reading experience. These results are consistent with tour observation in their performance in the experiment. Both objective and subjective results suggest that static reading zone presented on-sky and in sentences is the most ideal combination among the eight combinations.




**(a) Safety**

**(b) Reading Experience**

**Figure 9: Self-reported Preference: Percentage of Participants' Favorite Top 3 Combination in terms of Safety and Reading Experience**

# 6 GENERAL DISCUSSION

## 6.1 Adaptive Positioning Better at On-Road Position and Improve Paragraph Reading

Of the two positioning methods, we found the adaptive positioning approach is mainly advantageous when the reading zone was placed on-road, and particularly helpful for paragraphs, for shortening the participants' reaction times and not harming comprehension. We speculated that it particularly improved the reaction times and comprehension for paragraph presentation probably because the task resumption time for reading paragraph is longer, thus dynamically adapting the reading zone closer to the road scene helped reduce the time switching between the reading zone and the road scene. On the other hand, when applying the adaptive positioning to the reading-zone placed on-sky, not only that it led to lower reading comprehension, it also was considered by our participants to result in an unpleasant reading experience because of its constantly moving, making it hard to read and comprehend the articles. This finding contradicts those of previous research by Riegler et al. [53], in which dynamic positioning yielded better reading performance than its static equivalent. There are two main potential reasons for this discrepancy. First, in measuring reading comprehension, Riegler et al. used yes/no questions to test whether participants recognized the presented sentences as logically correct. In our study, on the other hand, we let participants read the whole chapter and measured their reading comprehension through test questions. We believe that, while this change increased the burden of reading, our scenarios more closely resembled real-world reading behavior. Second, because our research considered two other dimensions in combination with movements, interaction effects could have come into play (e.g., the dynamic movement particularly suited to on-road positions than on-sky ones, and that it helps better paragraph presentation than sentence presentation) that reversed the previous findings based on a single dimension. We believe these differences reveal more nuances that designers of reading interface for AVs should consider.

Therefore, in practice, we recommend that, by default, reading zones be displayed in the on-sky region and statically, so that the driver can see the nearby vehicles on the road clearly, and can easily read/browse the text. However, systems should still be susceptible to adjustment according to individuals' driving habits and preferences. Furthermore, we recommend that users be allowed to adjust the reading zone in the way they like. As well as meeting users' individual needs, this would allow the system to record driving and reading behavior and preferences, and to collect more contextual feedback from drivers.

## 6.2 Making the Reading Zone Farther Leads to Safer and Better Reading Experience

Despite the fact that the adaptive positioning approach could help users quickly react to the road scene, our quantitative results show that it does not lead to better reading comprehension. In addition, despite the fact that adaptive positioning makes eye gaze presumably nearly adjacent to the road scene, thus resulting in the lowest gaze-shift duration, reaction times is not shorter than when the reading-zone is placed on-sky. While this "seeing but not perceiving" could be due to different reasons, according to the participants, a plausible reason is the aforementioned overlapping problem, causing the attention of the sight to be chaotic and unable to switch quickly. As the reading zone and the nearby driving vehicles will overlap in on-road situation, participants might not see the nearby vehicles through the windshield. This could even further lead to the "looked, but failed to see" type of accident [22]. Participants also considered that "occlusion" was seen as making reading in an AV a risky activity. As a result, placing the reading zone on-sky can avoid the occlusion issue.

On the other hand, our quantitative results show that presenting a static reading zone on-sky, despite its longer distance from the road scene, does not lead to longer reaction times. In fact, drivers looking directly at the accident location were slower to notice an accident than those who only caught it in their peripheral vision [62], due to their reading zone being in the sky, showing a static reading zone on-sky, and particularly in sentences, on average led to one of the shortest reaction times. Furthermore, it also led to one of the best reading performance among all combinations. Consequently, these results tend to suggest that avoiding the reading zone from occluding road scene may be more vital than avoiding placing it farther from the road scene, in terms of either reaction times and reading quality.

To conclude with the ideal combination for presenting a reading zone on WSD in AV, according to our results, considering both safety, reading comprehension, and reading experience, we deem that the **Stc-Sky-Sen** combination, making the reading zone static, away from the road, even better at a position that makes the road scene falling in the peripheral vision [62], and presenting the article in sentences, maybe the most ideal reading modality on the WSD at present.

## 6.3 Limitations and Future Work

As an early study that explores these dimensions of a reading zone on the WSD in AVs, we did not conduct a comprehensive exploration of all possible dimensions, but sought to look for a reasonable set of dimensions to investigate why a specific combination would be more or less suited for being presented on the WSD in AVs. As a result, we explored only three dimensions of designing the reading zone, and within each dimension, we only investigated two variations. Exploring three dimensions already made interpretation of the interaction effect challenging; interaction effects involving four or more variables may be even more challenging to interpret. In addition, in our experiment, we adopted the adaptive positioning to the reading zone to the nearby vehicles or to the road, considering it is feasible for computer vision techniques to accomplish it. Yet, the adaptation approach we adopted is relatively naive, which can be sophisticated using more advanced detection techniques and algorithms. As the handover request was fixed at the 120th second of each round, participants might have learned when and where the accident would occur; however, since the time point of the accident is unknown to participants, also, we instructed them to immerse themselves in the autopilot, this may mitigate the learning effect of handover.

Although adaptive positioning does not favor participants to perform reading while moving, it would be interesting to investigate whether participants would need this feature when the probability of an upcoming handover exceeds a certain threshold (e.g., in high traffic). To understand how to support reading activities in AVs, a common multitasking activity during travel, we encourage future research to extend the current study and explore more variables that might affect safety and reading comprehension, such as parameters of the reading zone (size of the reading zone, font of the text, color of the text), driving scenarios (traffic, weather, backlighting, darkness, vehicle's motion), personal factors (fatigue, driving experience, multitasking-proficiency, etc.), or human factors of vehicle setting (the ergonomic design of buttons, windshield, steering wheel, and seat position). Finally, since the study was conducted in-the-lab, the ecological validity of the findings needs further research to validate.

# 7 CONCLUSION

Autonomous vehicles (AVs) are increasingly growing in the market. One of its essential features is auto-driving, allowing drivers to multitask, performing several non-driving related tasks/activities during the trip, including reading, one of the most common multitasking activities during travel. Considering that reading in AVs is a growing need due to the increasing prevalence of AVs, we deem it urging to explore ways to support and ensure the safety of this potentially everyday activity. We studied three dimensions of a reading zone on WSD, including dynamics, position, and text segmentation. Considering the fast advancement of computer vision that may make a reading zone adaptive according to nearby vehicles and road scenes, we simulated an adaptive positioning, but found it particularly beneficial for helping on-road reading zone that presents paragraphs. However, our general suggestion is to use a static reading zone that is presented on-sky and in sentences due to it yielding faster reaction and better reading comprehension. Given that this is only the start of exploring the design of reading interface in AVs, we encourage researchers to follow up the present study and explore other possibilities for supporting reading in AVs.

## ACKNOWLEDGMENTS

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