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Strategic Adaptation to Performance Objectives in a Dual-Task Setting

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Abstract

How do people interleave attention when multitasking? One dominant account is that the completion of a subtask serves as a cue to switch tasks. But what happens if switching solely at subtask boundaries led to poor performance? We report a study in which participants manually dialed a UK-style telephone number while driving a simulated vehicle. If the driver were to exclusively return his or her attention to driving after completing a subtask (i.e., using the single break in the xxxxx-xxxxxx representational structure of the number), then we would expect to see a relatively poor driving performance. In contrast, our results show that drivers choose to return attention to steering control before the natural subtask boundary. A computational modeling analysis shows that drivers had to adopt this strategy to meet the required performance objective of maintaining an acceptable lateral position in the road while dialing. Taken together these results support the idea that people can strategically control the allocation of attention in multitask settings to meet specific performance criteria.

Keywords: Multitasking; Cognitive modeling; Human–computer interaction; Driving; Performance tradeoffs; Performance operating characteristic

1. Introduction

How people control the allocation of resources to multiple concurrent tasks is a topic of considerable theoretical and practical interest (e.g., Navon & Gopher, 1979; Norman & Bobrow, 1975; Salvucci, 2005; Salvucci & Taatgen, 2008; Wickens, 2002). Previous research has shown that, in many multitasking situations, people tend to switch between tasks on the completion of a subtask (e.g., Bailey & Iqbal, 2008; Miyata & Norman, 1986; Payne, Duggan, & Neth, 2007; Salvucci & Bogunovich, 2010). This is a particularly

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efficient method for managing the demands of multiple tasks because workload decreases on the completion of a subtask (Bailey & Iqbal, 2008), mental resources become available for other processes (Salvucci & Taatgen, 2008; Wickens, 2002), and it avoids resumption costs (Altmann & Trafton, 2002). But what if waiting to switch tasks until a subtask boundary led to poor performance on a more important task?

In this study, we investigate whether dual-task interleaving is confined to subtask boundaries. To address this question, we use a dialing while driving dual-task paradigm. Many studies have investigated the impact of cellphone dialing on driving performance (e.g., Alm & Nilsson, 1995; Brookhuis, De Vries, & De Waard, 1991; Brumby, Salvucci, & Howes, 2009; Horrey & Lesch, 2009; Reed & Green, 1999; Salvucci, 2005). Typical results show that when drivers are required to dial a standard North American phone number, for instance, they tend to interleave at chunk boundaries in the number (e.g., 123, steer, 456, steer, 7890). It has been argued that this pattern of dual-task interleaving emerges because telephone numbers tend to be represented as distinct chunks in memory, and after dialing one chunk of digits, there is a short delay that can be exploited to check on the road, whereas the next chunk is retrieved from memory (Salvucci, 2005; Salvucci & Taatgen, 2008).

An alternative account of this behavior is that people select strategies to meet a desired dual-task performance objective. Brumby et al. (2009) used a computational model to derive performance predictions for a range of different dual-task interleaving strategies for dialing a standard North American phone number while driving. It was shown that dialing three or four digits at a time is a particularly efficient strategy because any more interleaving incurs additional time costs without significant improvement in lane keeping, and any less interleaving sacrifices safety. Because the number used in many driver distraction studies (e.g., Brumby et al., 2009; Salvucci, 2005) was made up of chunks of three and four digits each, it is not possible to determine whether the observed dual-task interleaving strategy was shaped by the representational structure of the number, or whether participants were adapting their behavior to meet a desired dual-task performance objective. Here, we redress this issue by having participants dial a telephone number that has many more digits per chunk.

An experiment is reported in which participants dialed a UK-style telephone number while driving a simulated vehicle. The benefit of using a UK-style number is that it has many more digits per chunk (i.e., 12345-678901) than a typical US-style number (i.e., 123-456-789). If drivers were to interleave only at the chunk boundary when dialing the UK-style number (i.e., after the first five digits), then we might expect the vehicle to drift far from the lane center. Although this might be tolerable if the participant were giving priority to dialing quickly, we might expect participants to interleave their attention between tasks more frequently if they were choosing to prioritize safer driving.

Speed-accuracy tradeoffs are a common and often adaptive feature of human decision-making (Edwards, 1965), and a large body of empirical work has demonstrated that people can make explicit decisions about how to allocate attention to different tasks in multitask settings by prioritizing the performance on one task over another (e.g., Brumby et al., 2009; Gopher, 1993; Gopher, Brickner, & Navon, 1982; Horrey, Wickens, & Consalus, 2006;

Levy & Pashler, 2008; Navon & Gopher, 1979; Wang, Proctor, & Pick, 2007). In the current study, we consider how changes in task objective affect the decision about when to interleave attention between tasks. Instructions and feedback were manipulated to encourage participants to prioritize either rapid completion of the dialing task or safer driving. As a proxy for driver safety, we consider how well the driver is able to maintain a central and stable lane position while driving (indexed by the vehicle's lateral deviation from the lane center). We use Brumby et al.'s (2009) modeling framework to derive performance predictions for various dual-task allocation strategies to determine whether interleaving before the chunk boundary is necessarily required to meet the performance objective of maintaining an acceptable lateral position in the road while dialing.

2. Experiment

2.1. Participants

Fourteen participants (four female) from the subject pool at University College London participated for monetary compensation. Participants were between 19 and 28 years of age (M = 22.9 years). All had a valid driver's license for at least 2 years.

2.2. Materials

The driving task required participants to navigate the center lane of a straight, three-lane highway environment. The simulation environment was displayed on a 30-inch monitor and controlled by a Logitech G25 Racing Wheel (Logitech Europe S. A., Morqes, Switzerland). Participants were required to steer the vehicle to maintain a central lane position, with the vehicle's speed held at a constant 88.5 km/h. To encourage safe lane keeping, safety cones were placed at either side of the driver's central lane. Noise was added to the vehicle dynamics, causing it to gradually drift in the lane. This meant that the participant had to actively control the vehicle's lateral position and heading to maintain a central lane position. To index this, the simulator logged both the vehicle's lateral deviation from the center of the lane and also the angle of the steering wheel at a rate of 200 Hz.

The dialing task required participants to enter a single UK-style phone number (i.e., 07854-325698) on a mobile phone (Nokia 6300). The phone was positioned to the left of the driver in a hands-free cradle mounted on the desk. Participants were required to dial a ''#'' before and after entering the number. Incorrect entries had to be corrected by pressing the ''*'' button to delete the last digit from the string of digits. This additional time cost to correct entry errors served to encourage accurate dialing.

2.3. Design

A single-factor within-subjects design was used, in which participants were instructed to either focus on completing the secondary dialing task as quickly as possible (the dialing-focus condition) or to focus on keeping the vehicle as close as possible to lane center (the steering-focus condition). The main dependent measures were time to correctly enter the number for the dialing task, and the vehicle's lateral distance from lane center for the driving task. To help identify dual-task strategy, we also consider the frequency of steering movements in between each successive keypress.

2.4. Procedure

We used an extensive training session to ensure that participants learned the telephone number in the intended representational chunk structure. Participants practiced dialing each chunk of digits separately. That is, participants were given the opportunity to dial the first ''07854'' part of the number many times for 3 min, before being given the opportunity to practice entering the second ''325698'' part of the number for another 3 min. After this practice period, participants were given 10 trials to dial the complete number. The number was presented on the simulator screen with all digits covered, except for those from the current chunk (e.g., 07854-xxxxxx). Participants had to dial this chunk on the phone. As soon as a chunk was dialed, it was covered up and the next chunk was revealed (e.g., xxxxx-325698).

The dialing practice was followed by ten 30-s driving practice trials. After this, participants performed two blocks of experimental trials. For each block participants completed (a) five single-task dialing trials, (b) five single-task driving trails, and (c) 20 dual-task trials under one of the two priority instructions (i.e., steering-focus or dialing-focus). The second block had the same structure as the first, but with a different priority instruction for dual-task trials. The order of priorities was randomized and counterbalanced across participants. The total procedure took about 60 min.

For the single-task dialing trials, participants were instructed to dial the number as quickly as possible. Feedback was given on the total dialing time (the time between the two presses of the '#' sign) after each trial. After the fifth trial, average performance was reported.

For the single-task driving trials, participants were instructed to keep the vehicle as close to lane center as possible (minimizing lateral deviation) over a fixed 30-s period of driving. At the end of each trial, participants received feedback showing the root mean-squared error (RMSE) lateral deviation of the vehicle from lane center over the 30-s trial. Every fifth trial, the average performance was reported. Providing such feedback during the training phase allowed participants to become accustomed to the lateral deviation measure that was used to represent the driving performance.

For dual-task trials, participants dialed the number while driving. Participants received a specific instruction to either prioritize safe driving (steering-focus) or rapid completion of the dialing task (dialing-focus). To emphasize these instructions, participants received feedback at the completion of every trial on the relevant variable. Specifically, participants in the steering-focus condition received feedback about the vehicle's RMSE lateral deviation, whereas participants in the dialing-focus condition received feedback on the time taken to dial the number correctly. Average performance was given every fifth trial.

3. Results

The primary dependent measures were dialing time and the lateral deviation of the vehicle from the center of the lane. Of the 650 dual-task trials, we excluded data from 85 trials in which participants made an error on the dialing task (mean participant error-rate was 15%, $SD = 11\%$).

Fig. 1 shows a data plot where the elapsed time of each keypress from the start of dialing (represented on the x-axis) is plotted against the corresponding absolute lateral distance of the vehicle from lane center (represented on the y-axis). As expected, dialing time was quicker in the dialing-focus condition ($M = 5.02$ s, $SD = 1.39$ s) than in the steering-focus condition ($M = 7.69$ s, $SD = 1.81$ s), $t(13) = 7.00$, $p < .001$, resulting in overall worse RMSE lateral deviation in the dialing-focus condition ($M = 0.74$ m, $SD = 0.30$ m) than in the steering-focus condition ($M = 0.50$ m, $SD = 0.18$ m), $t(13) = 4.20$, $p < .001$. More interestingly, the data in Fig. 1 show that when participants prioritized safer driving, there was a clear reduction in lateral deviation after the third digit had been entered. This correction in lateral deviation occurred well before the chunk boundary in the number.

To support the observation that there was a reduction in lateral deviation before the chunk boundary in the steering-focus condition, we performed a 2 × 11 (Task Priority × Digit Position) mixed factorial ANOVA on lateral deviation data. As expected, we found significant main effects of task objective, $F(1, 13) = 17.65$, $p < .001$, and digit position, $F(10, 13) = 2.42$, $p < .05$, on lateral deviation. More important, there was a significant interaction between task objective and digit position, $F(10, 130) = 4.37$, $p < .001$. Follow-

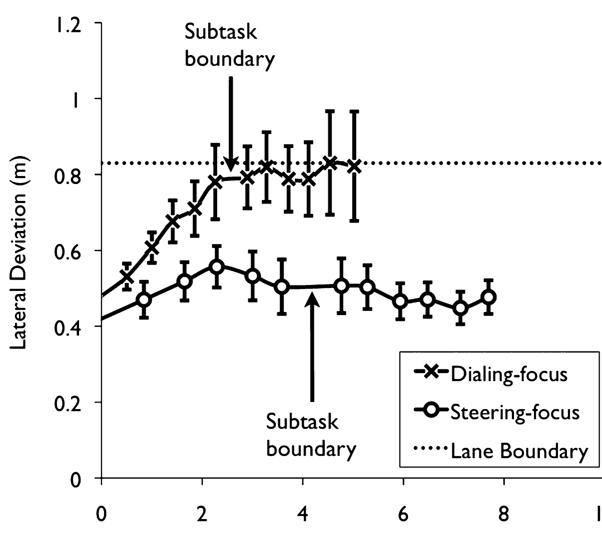

Fig. 1. Data plot shows changes in vehicle lateral deviation between consecutive keypresses (07854-325698) under varying dual-task performance objectives. Arrows highlight the subtask boundary for the dialing task. Error bars represent standard error of the mean.

up tests of the simple effect of task priority showed that the divergence in lateral deviation between the two conditions occurred at the third-digit position; that is, there was no significant difference in lateral deviation between the two conditions at the first and second keypress (p = .23 and .09, for the first and second keypress, respectively), but after the third keypress, the vehicle was significantly farther from the lane center in the dialing-focus condition than the steering-focus condition (p < .05, for the third through eleventh keypress).

The data in Fig. 1 show that, when participants were prioritizing safer driving, the vehicle reached its maximum lateral distance from the lane center on dialing the third digit. This suggests that participants were attending to the driving task before they reached the chunk boundary. To be sure that this was not an artifact of considering average data, we considered the frequency of trials that the maximum lateral deviation was found at a particular digit position. These data are shown in Fig. 2. It can be seen that, for both conditions, there were two peaks in the distribution. As we might expect, there was a large set of trials where the vehicle was farthest from the lane center at the completion of dialing (i.e., the right peak in the figure at Digit Position 11). Interestingly, there is a second peak for each condition, representing trials in which the vehicle was farthest from the lane boundary partway through the dialing task. The peak of this second distribution varied between conditions: In the dialing-focus condition, the peak was before the chunk boundary at Digit Position 5, but for the steering-focus condition, the peak occurred before the chunk boundary, at Digit Position 3.

To be sure that these improvements in vehicle control were due to active steering on the part of the participant, we next consider when there were periods of active steering control. We define a steering movement event as any period where there was a change in the angle of the steering wheel after at least three consecutive stable samples (at a frequency of 50 Hz). Fig. 3 shows the average frequency of steering movements for each condition at each digit position. As expected, we found that participants steered more in the steering-focus condition (M = 15.23 events, SD = 4.48 events) than in the dialing-focus condition (M = 9.01 events, SD = 2.86 events), F(1, 13) = 33.47, p < .001. To identify at which specific digit positions participants chose to steer more in the steering-focus condition than in the dialing-focus condition, we considered the simple effect of task priority at each digit

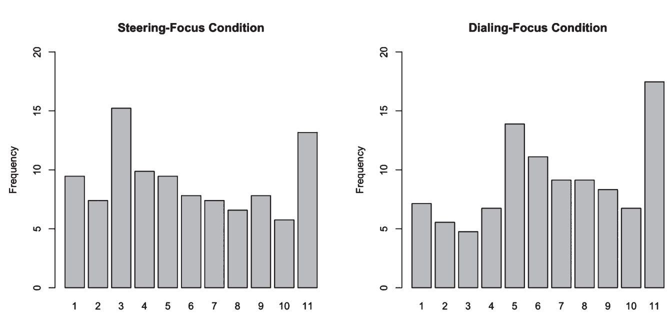

Fig. 2. Histograms show the frequency of trials that the maximum lateral deviation was found at a particular Digit Position for each focus condition.

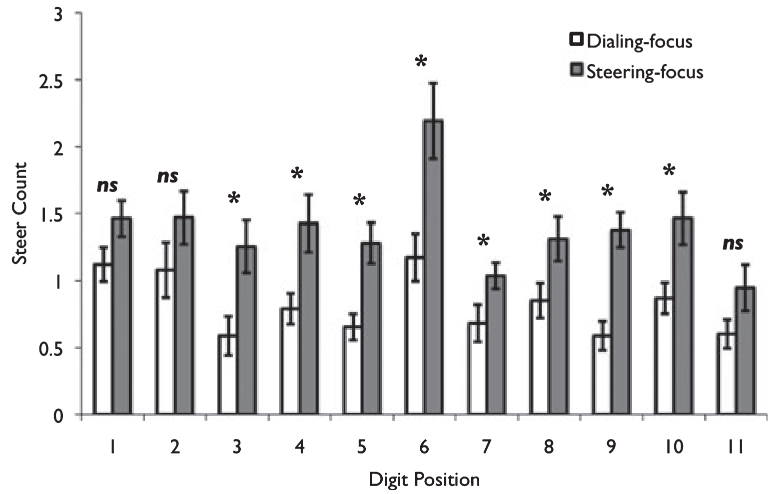

Fig. 3. Bar chart shows the frequency of the average number of steering movement events for each condition at each digit position. Error bars represent standard error of the mean. *denotes $p < .05$; *ns* denotes a nonsignificant difference between conditions.

position. This analysis shows that there was no significant difference in steer count frequency between the two priority conditions at the first- and second-digit positions ($p = .07$ and .15, for the first and second keypress, respectively). But consistent with the lateral deviation data, after the third keypress there were significantly more active steering movements in the dialing-focus condition than the steering-focus condition ($p < .05$ for the third through tenth keypress, with the exception of the final keypress, where there was no effect of task priority, $p = .07$).

4. Discussion

A study was conducted in which participants manually dialed a well-practiced UK-style telephone number while driving a simulated vehicle. Results show that task interleaving was not confined to the chunk boundary of the secondary dialing task, but that participants could flexibly adapt their strategy to give greater priority to one task or the other. In particular, when participants were instructed to prioritize driving performance, the steering and lateral deviation data show that participants tended to actively attend to the driving task before the chunk boundary. This increase resulted in better lateral control of the vehicle, but at the cost of dialing task time. In contrast, participants in the dialing-focus conditions appeared to wait until the chunk boundary before attending to the driving task, which allowed the dialing task to be completed more rapidly but at the cost of causing the vehicle to drift farther from the lane center.

The results of our study suggest that people can flexibly adapt dual-task interleaving behavior to meet specific performance objectives. However, one assumption that has been made is that it was not possible for participants to maintain lateral control of the vehicle by returning their attention to steering control only at the chunk boundary. For instance, what if the driver were to simply invest a considerable amount of time just at this point to stabilize the vehicle? Could such a strategy account for the observed performance data?

To address these questions, we use Brumby et al.'s (2009) modeling framework to understand how different dual-task allocation strategies affect critical performance metrics, namely, dial time and driver safety. This approach of explicitly considering the performance tradeoffs involved for choosing between various dual-task allocation strategies is similar to that of defining a performance operating characteristic (Navon & Gopher, 1979; Norman & Bobrow, 1975). A specific question we sought to address with this modeling framework is whether task interleaving before the chunk boundary was necessarily required to meet the performance objective of maintaining an acceptable lateral position in the road while dialing.

5. Computational model

Our modeling approach (Brumby, Salvucci, & Howes, 2007; Brumby et al., 2009), which is based on the cognitive constraint modeling approach (Howes, Lewis, & Vera, 2009), focuses on deriving performance predictions for various strategies for completing the dialing task while driving. The model represents basic task operators (e.g., dialing a single digit, or performing a steering control update) as discrete processing units that are limited by a serial bottleneck. This means that the dialing task interferes with steering control processes.

The model simulates a simple driving environment, similar to that experienced by participants in the study, in which a vehicle is moving at a constant speed down a straight road. The model adjusts the heading (or *lateral velocity*) of the vehicle once every 250 ms based on its lateral deviation (LD) from the center of the lane,

$$\text{Lateral velocity} = 0.2617 \times \text{LD}^2 + 0.0233 \times \text{LD} - 0.022. \tag{1}$$

There is an upper bound of 1.7 m/s on lateral velocity, reflecting the fact that the steering wheel has a maximum angle. This mathematical model, described in more detail in Brumby, Salvucci, et al. (2007), is based on an analysis of steering control data taken from previous studies (Salvucci, 2001; Salvucci & Macuga, 2002) and captures the basic idea that as the vehicle strays closer to the lane boundary, drivers react by making sharper corrective steering movements, which in turn increase the lateral velocity of the vehicle, returning it to a central lane position more rapidly. To account for variability in human steering control, a random value, sampled from a Gaussian distribution with $M = 0.00$ m/s and $SD = 0.10$ m/s, is added to the value of the updated lateral velocity given by the steering control model (Eq. 1). To simulate the driving environment, we permute the vehicle's heading every 50 ms with a value drawn from a Gaussian distribution with $M = 0.00$ m/s and $SD = 0.13$ m/s. The variance of this noise distribution is the only free parameter in the model, which was fit by comparing the models performance with data from the dialing-focus condition. We assume that dialing interferes with the steering control process.

The dialing task is modeled at the granularity of the time taken to execute individual keypresses. We derive estimates for the time taken to execute an individual keypress from the single-task dialing data. We found that the average interval between each keypress was 400 ms, with the exception of the first keypress of each chunk (i.e., the first and sixth keypress), which were 500 ms each. We assume that switching attention between tasks takes an additional 200 ms. Furthermore, we assume that disrupting the chunk structure of the dialing task carries an additional time cost of 100 ms to retrieve state information from memory. With the basic time cost parameters for the dialing task set, we consider various dialing strategies and how these might interfere with the normal steering control process.

The dialing task required participants to dial an 11-digit number. After dialing each digit, the driver can either dial the next digit or perform a corrective steering movement. This gives 1,024 (2^{10}) different dual-task interleaving strategies. For each strategy, we systematically varied the number of steering updates that the model made before returning to dialing. Values ranged from 250 to 5,000 ms, with intervals of 250 ms. The number of steering updates was kept constant within runs (but varied between runs) to limit the amount of simulations required. This gives a fairly large set of 20,461 alternatives (out of the full space of 21^{10} alternatives). Each alternative was run 200 times to give reliable measures of central tendency for the critical performance metrics. For each model run, the simulated vehicle started at 0.45 m from the lane center (a value fitted from the empirical data).

6. Model results

Fig. 4 shows the average RMSE lateral deviation and dialing task time for each of the 20,461 dual-task interleaving strategy alternatives. It can be seen that the model predicted a performance tradeoff between strategies that completed the dialing task quickly but had relatively poor lane-keeping performance, and those that completed the dialing task slowly but had relatively better lane-keeping performance. The shape of the tradeoff curve predicted by the model is noteworthy. There is a clear tipping point where improvements in lane-keeping performance become smaller with increased time. The human data for the steering-focus condition lie at this tipping point in the tradeoff curve, suggesting that participants adapted their strategy to meet the performance objective of minimizing lateral deviation while completing the secondary dialing task in a reasonable amount of time (note that time is represented on a logarithmic scale). Data from the dialing-focus condition lie close to the leftmost extreme of the strategy space, where faster performance is associated with poor lane keeping.

The model can be used to determine whether interleaving before the chunk boundary was required in order to reach the tipping point in the tradeoff curve. Specifically, it might have been possible to achieve the observed RMSE lateral deviation by returning attention to steering control only once while dialing, at the chunk boundary, and dedicating a lot of time to steering control at this point. To test this idea, Fig. 4 highlights the performance of a ‘‘chunk-interleaving only’’ strategy with varying time given up to steering control. It can be seen that even when substantial periods of time were given up to steering control (up to 5 s), RMSE lateral deviation never reached the tipping point in the tradeoff curve, nor did

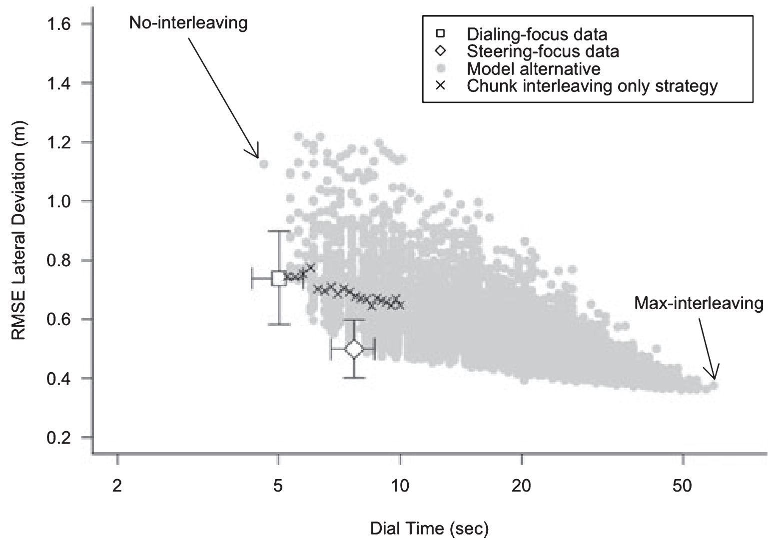

Fig. 4. Data plot shows predicted dial time and RMSE lateral deviation for modeled strategies and human data under varying dual-task performance objectives. Error bars represent 95% confidence intervals.

the performance fall within the 95% confidence intervals (CIs) of the human data from the steering-focus condition. Moreover, of the 586 strategies that fell within the 95% CIs of the human data, all but one of these strategies performed a steering update before the chunk boundary. Taken together, this modeling analysis suggests that participants had to interleave tasks more often than that allowed by the chunk boundary in the dialing task to meet the performance objective of minimizing vehicle lateral deviation while dialing.

7. General discussion

This study provided a critical test for the theory that, in dual-task settings, people use the completion of a subtask as a cue to switch between tasks (e.g., Salvucci, 2005). The data presented here suggest that people are prepared to suspend tasks to interleave at a rate that guarantees that performance objectives are met. In our case study of dialing while driving, dialing was not necessarily interleaved at chunk boundaries. Instead, participants were prepared to monitor driving performance outside of the explicit chunk structure of the secondary dialing task when it was required to meet the set task objective. These findings support the idea that people can strategically allocate attention in multitask settings to meet different performance objectives (e.g., Brumby et al., 2009; Gopher, 1993; Gopher et al., 1982; Horrey et al., 2006; Levy & Pashler, 2008; Navon & Gopher, 1979; Norman & Bobrow, 1975; Wang et al., 2007).

To explain the observed change in dual-task strategy, we used an existing framework for modeling driver distraction effects (Brumby, Howes, & Salvucci, 2007; Brumby et al., 2009). The model represents basic task operators as discrete processing units that are limited by a serial bottleneck. The model allowed us to derive performance predictions for various dual-task allocation strategies, showing that interleaving before the chunk boundary is required to meet the performance objective of maintaining an acceptable lateral position in the road while dialing.

Moreover, the modeling helps explain the observed shift in task performance from when participants prioritized the dialing task to when they prioritized driving. The model predicts a classic dual-task performance tradeoff (Navon & Gopher, 1979; Norman & Bobrow, 1975) between safer driving and shorter dialing time. Interestingly, the tradeoff curve has a clear tipping point, after which improvements in lane-keeping performance become relatively small with increased time investment. Human performance data from the steering-focus condition lie close to this tipping point. We argue that theories of human multitasking behavior should be sensitive to the role of performance objectives in shaping behavior.

There are at least two directions for developing the experimental methodology. First, a performance-based payoff function (Howes et al., 2009) could be used to explicitly define how tasks should be traded against one another. In the current study, participants were instructed to prioritize safe driving over dialing, but without an objective performance criterion we cannot determine how these instructions were interpreted. Second, further strategic adaptations of behavior might emerge with increased veracity of the driving simulator (Reed & Green, 1999). As it stands, the driving task was relatively simple, requiring participants to only control vehicle heading. There is evidence that drivers tend to compensate for the demands of performing a secondary in-car task by reducing their speed (Cnossen, Meijman, & Rothengatter, 2004). However, drivers seem to be incapable of holding off until an appropriate moment to initiate secondary tasks, which suggests that rational behavior collapses at higher levels of planning (Horrey & Lesch, 2009).

In conclusion, the work presented in this study shows that people do not solely interleave at the natural breakpoints. Instead, people can strategically control the allocation of attention in multitask settings to meet specific performance criteria.

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