Driver distraction, crosstalk, and spatial reasoning

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The hypothesis is explored that driving performance is not always influenced negatively by a secondary, unrelated, spatial reasoning task. The precise influence also depends on the specific spatial cues used in this task, compared to those currently emphasized by the primary driving task. In a laboratory experiment, participants were presented with questions about spoken (familiar) city names while driving. The questions either required them to reason spatially about the cities or to process the same city names only acoustically (i.e., remembering and repeating one of the names). Amount of driver distraction was measured by means of a standardized tool called the Lane Change Task (LCT) using a PC-based driving simulator. Results of the experiment showed that the spatial reasoning secondary task was more distracting than the acoustic one. In addition, participants performed worse on the LCT when switching to a right lane than when switching to a left lane. It is concluded that the results confirm an interpretation in terms of (in)compatible spatial cues emphasized simultaneously by primary and secondary task, but that alternative interpretations are also possible. The moderating influences of two cognitive ability variables on, and potential practical applications of, these findings are also addressed.

1. INTRODUCTION AND PROBLEM STATEMENT

An increasing number of automobile accidents is attributed to distracted driving. The percentage of accidents with such origin varies from 5 to over 25%, depending on the type of study (traditional crash studies or naturalistic driving studies) and the definition of distraction utilized by the study (Gordon, 2009; Neale *et al.*, 2005). Naturalistic studies arrive at percentages as high as 23% for crashes due to the performance of non-driving related secondary activities a few moments before the crash. These activities include personal grooming, and reaching for some object in the car. Moreover, there is evidence this percentage would be even higher if inattention-based crashes were included in the crash statistics (i.e., paying insufficient attention to the forward roadway due to daydreaming or other internal, but invisible activities).

Obviously, when driving, not all sources of distraction can be avoided. However, knowledge about the human driver can help reduce the size of the distraction problem, for example by appropriately designing car-based equipment and procedures for its usage, but also by training and reinforcing drivers to behave prudently and responsibly with respect to the use of distracting equipment or activities.

Though driver distraction can usefully be attributed to some kind of interference between a secondary task (driving-related or not) and the primary driving task, there are multiple sources of such dual-task interference in the driving context. Moreover, many psychological mechanisms have been proposed for explaining the nature and size of the interference. In an attempt to clarify these issues, we start by distinguishing structural interference from cognitive interference. *Structural interference* is based in the physiology of the sense organs. It refers to the influence of physiological limits on the ability of people to perform two or more tasks simultaneously (Pashler & Johnston, 1998). *Cognitive* *interference*, on the other hand, refers to those types of interference that are observed when some or all subtasks of the time-shared tasks require information processing (Kujala, 2010). Cognitive interference, in turn, can be divided into task-independent interference and task-dependent interference. The latter type of interference usually refers to the interference caused by task similarity.

One particular type of similarity-based interference is also known as *crosstalk* (Navon & Miller, 1987): keeping simultaneous information processing streams (tasks) separate becomes difficult if they contain stimuli with overlapping attributes (e.g., color or direction). Such coordination is especially difficult if the overlapping attributes must be kept in working memory for some time, do not (always) take on the same value and are relevant to both information processing streams (Hommel, 1998; Lien & Proctor, 2002; Pashler, Johnston, & Ruthruff, 2001). For example, color is a relevant stimulus dimension for task A, but also for the (unrelated) task B which demands attention at more or less the same time (or in close succession) as task A. In that case, stimuli tend to trigger responses in the "wrong" stream which conflict with the correct response for that stream. This is similar to the Stroop task (Stroop, 1935) and the Simon effect (Simon, 1990) in single-task conditions.

Though the empirical evidence for crosstalk is rather robust, disagreement exists in the literature with regard to the generality of, and the theoretical explanation for, this phenomenon. Explanations are based in theories varying from *limited capacity models* (Pashler, Johnston, & Ruthruff, 2001), to *multiple resources theory* (Wickens, 2002), to the concept of *attention sharing* (Navon, 1984, 1985), and to the *theory of multimodal spatial attention*. According to the latter account, shifts of spatial attention in one sensory modality (e.g., vision) tend to be accompanied by corresponding covert shifts in other modalities (e.g., audition) (Spence & Driver, 2004; Driver & Spence, 1998). These attentional shifts may be triggered by external events (exogenous attention shifts) or by internal events (e.g., intentions or thoughts: endogenous attention shifts). Therefore, this theory may explain crosstalk to the extent that the stimulus attributes causing crosstalk are spatial in nature.

Regarding the empirical conditions necessary for crosstalk to be observed, there is evidence that time-shared tasks are less vulnerable to crosstalk with certain types of display design and task configuration (Elio, 1986; Carlson & Sohn, 2000). Under some circumstances, task similarity also results in *improved*, rather than reduced, dual-task performance. Specifically, time-sharing efficiency may improve if tasks share some common display property, processing routine, mental set, or timing mechanism (Fracker & Wickens, 1989; Duncan, 1979). These findings probably reflect the fact that task reconfiguration becomes simpler, going from task to task, when the tasks are structurally identical or similar.

This article describes a laboratory experiment in which one particular type of crosstalk was studied in the context of driver distraction. Specifically, the effect on driving performance was studied of having simultaneous activation in working memory of semantically related spatial codes, these codes either being invoked by a spatial reasoning auditory secondary task or a concurrently performed primary (driving) task. In addition to a spatial reasoning version, an acoustic version of an otherwise identical secondary task was employed. This acoustic version served as a baseline against which to assess the distracting effect of the spatial reasoning part of the first version, as the two versions only differed with respect to the amount of spatial reasoning they imposed on the participants. Driver distraction was measured by means of a standardized tool, called the Lane-Change Task (LCT).

The rationale for studying this particular spatial reasoning task as a secondary task was that, though cognitive interference of a spatial nature has already been studied before in a driving context (Patrick & Elias, 2009), the distracting effect of semantically related spatial memory codes on driving performance has not. Moreover, we wanted to test the generality of the observation that not only physically related items, but also items belonging to the same semantic category may cause crosstalk (Hirst & Kalmar, 1987). Specifically, in this experiment the hypothesis was tested that cardinal spatial cues such as “east” and “west” belong to the same semantic category as (and, therefore, may interfere with) egocentric spatial cues, such as “left” and “right”. The moderating influence of two cognitive ability variables was also investigated in this study: *useful field of view* (UFOV) and *task-switching ability (TSA*).

From a practical point of view, spatial reasoning can be considered an ecologically valid secondary task, because it can be linked to the use of in-car GPS-devices, to navigational conversations, or to reading a map while driving. Therefore, the results of this experiment may also have practical applications.

2. HYPOTHESES

From the multiple resources theory (Wickens, 2002) and from the functional distance theory (Kinsbourne & Hicks, 1978) it follows that spatial reasoning about familiar city names must be a more distracting secondary task to drivers than acoustically processing the same stimuli (i.e., remembering and repeating the first of two spoken city names). This hypothesis is also consistent with the outcomes of another study (Patrick & Elias, 2009) showing the distracting effect of performing an irrelevant mental navigation task while driving. Functional distance theory states that the longer the distance between the brain parts that are involved in unrelated information processing tasks, the smaller the amount of interference to be observed between the tasks. This theory is also supported by recent neurological evidence (Newman, Keller, & Just, 2007). Therefore:

Hypothesis 1. The spatial reasoning version of the secondary task interferes more with the driving task than the acoustic version of the same task.

Spence and associates have shown that cognitive spatial tasks could have an interfering effect on the spatial parts of the driving task, if the two types of task emphasize different spatial locations (Spence & Read, 2003; Spence & Driver, 2004; Spence & Ho, 2008).

In our study, the spatial reasoning version of the secondary task forced participants (as we will see) to think about the east-west orientation of familiar cities. During some parts of the experiment, the spatial memory codes induced by this secondary task coincided or conflicted with the primary task, which required participants to steer to the right or to the left, depending on the nature of a symbolic switch sign that was encountered in the LCT. This is also based on Hirst and Kalmar (1987) who showed that even items belonging to the same semantic (symbolic) category may cause crosstalk between unrelated information processing streams. Specifically, it was expected that left-going maneuvers would be facilitated by thinking about the west (left)-side part of a mental map, whereas right-going maneuvers would interfere with the same kind of thinking. For the acoustic version of the secondary task, no such main effect of steering direction was expected. Therefore:

Hypothesis 2. Driver distraction is smaller if the spatial directions simultaneously emphasized by secondary task (spatial reasoning version only) and primary task coincide than when they conflict with each other.

Zooming in more precisely on the specific periods of the experiment when participants were actually involved in spatial reasoning about the secondary task stimuli, we expected that the effect described by Hypothesis 2 (main effect of steering direction) is stronger for those phases of the spatial reasoning secondary task where such reasoning was actually taking place, as compared to the remaining phases. Again, for the acoustic version of the secondary task, no such direction * phase interaction was expected. Therefore:

Hypothesis 3. When actually involved in spatial reasoning, the distracting effect of a spatial reasoning secondary task (as described by Hypothesis 2) will be larger than when no such reasoning is taking place.

The moderating influences of UFOV and TSA on hypotheses 1, 2 and 3 were studied in an exploratory sense.

3. METHOD

3.1 Participants

Eleven female and nine male participants in the age range 20-76 participated in the experiment. They were all licensed drivers with (corrected no) normal vision and hearing. Most of them were students who received course credit points (or €7) for their participation. However, about six participants were recruited through advertisements. These participants were offered a €10 euro reward. In a background questionnaire, participants indicated that their average age was 35 years, that they had, on the average, 15 years of driving experience, and that they made (on the average) slightly less than 3 rides per week (see also Table 1).

Participants were randomly (but evenly) assigned to one of two blocks of conditions (block 1 and block 2, to be explained below under *3.3. Procedure and tasks*). The experiment lasted approximately 50-60 min.

3.2 Stimuli and equipment

The participants´ driving skills were measured with the *Lane Change Task* (LCT) (Mattes, 2003). The LCT ran on a Pentium 4 Dell PC equipped with a special graphics card. The road image generated by the LCT was projected on a wide (42in diameter) TFT LCD monitor. Participants were seated in an authentic car seat with the LCT-screen at eye height, controlling the LCT using a game steering wheel and foot pedals. The distance between the participant’s face and the centre of the wide monitor was about 1.70 m (see Figure 1). For each experimental condition participants completed one track, corresponding to a straight road segment of 3 km.

Insert Table 1 and Figure 1 about here

At unpredictable travel times and distances, two identical switch signs would be encountered on each side of the road, instructing the participant to move to the left, middle, or right lane (see Figure 2). The destination lane was always different from the departure lane. After switching, participants were required to drive in the middle of the new lane as well as possible. In total, 18 signs were used for each track. Different signs were used for different track variants. However, in this experiment only 5 different track variants were used, these were the same for each participant and were always presented in the same order.

Insert Figure 2 about here

The maximum driving speed was set at 65 km/h and participants were asked to drive as fast as they could. LCT-performance on any track was calculated off-line by LCT-analysis software and was expressed as the average amount of deviation (in meters) between a normative model and the actual driving course. See Figure 2 for the values of the parameters that belonged to the specific normative model that was used in this experiment.

In the secondary task, pairs of familiar Dutch city names were spoken through a set of head-phones. In one version of this task, for each pair participants were to state which city had the most western orientation. This was called the *spatial reasoning* version of the secondary task (SR). All cities to be compared were at least 15 km apart in east-west direction. Names and locations of cities had previously been familiarized in the *short topography training-and-test session* (see below). Because of the multitude of possible pairs it was assumed that the answers to the spatial questions were arrived at through spatial reasoning and could not have been memorized in the training-and-test session. In a second version of the secondary task, the same city names were presented, but now participants were merely to repeat the name of the first city of each pair. This was called the *acoustic* version of the secondary task (AC). For each participant and for both versions, pairs were chosen randomly from a list of 30 different pairs, each composed of two names taken from a list of 16 different city names.

Both versions of the secondary task were programmed in Eprime and ran on a Pentium 4 Dell PC with a standard 17 in monitor. This PC was different from the one used for running the LCT. Answers were spoken out loud by the participant and copied by the experimenter into the secondary task PC using a keyboard.

Useful field of view was measured using the PC-based version of the UFOV, subtest 3 (Ball & Owsley, 1993).

Task-switching ability was measured using the TSA-IAT (TSA, for short). This test uses the paradigm of an *implicit association test* (Back, Schmukle, and Egloff, 2005). It is assumed to measure a person´s ability to switch between task sets, an ability often associated with attentional (or executive) control and with general intelligence. The TSA was translated from German into Dutch by this author and implemented in Eprime. Because readers may not be familiar with this test, its logic is briefly described below.

On each trial a centrally presented item must be classified as quickly as possible by choosing between a category name shown on the left-hand side and a category name on the right-hand side of the screen. Two types of categorization are used on alternative trial blocks: alphabetical (choosing between letters and words) and numerical (choosing between numbers and arithmetic expressions). However, on certain trials, two category names are shown on the left-hand side (instead of one), and two other names on the right-hand side. These same-side categories are either semantically compatible (e.g., numbers and arithmetic expressions) or incompatible (e.g., numbers and words).

The participant must understand from the context which type of categorization is relevant to the classification task on these special trials: numerical or alphabetical (depending on the category the target item belongs to). The difference between the mean reaction times for incompatible and compatible trials is taken as a person's task-switching ability score (the higher the score, the worse the task-switching ability). In our experiment, the D_1-measure ("improved scoring algorithm"), described by Back, Schmukle, and Egloff (2005), was used for computing a person's TSA-score. This measure expresses the above-mentioned difference in reaction times as a fraction of the standard deviation of all reaction times obtained for that person.

Both UFOV and TSA ran on the same Pentium 4 Dell PC that was used for running the secondary tasks.

3.3 Procedure and tasks

First, participants read a brief written instruction and were asked to sign an informed consent form. Next, they filled out a background questionnaire and received a *short topography training-and-test session.*

The purpose of the topography session was to familiarize participants with the city names and locations to be used in the spatial reasoning version of the secondary task, and to minimize individual differences in this familiarity. A schematic map of The Netherlands was presented in which 16 cities were shown. Participants were given 2 min to memorize this map. After this, they were presented with an empty test map and were asked to answer a series of paired-associates questions to test how well they had learned the city locations (see Figure 3). Not until they had passed this test without assistance (i.e., 100% accuracy in matching city numbers with city names), were the participants allowed to proceed to the experiment proper.

Second, for half of the participants, the UFOV was administered. For the remaining participants, the TSA was administered.

Third, participants were familiarized with the LCT, completing one track without secondary task while receiving instructions and explanations from the experimenter. After this, participants were asked to complete four LCT-tracks on their own. They started with the first control track (C1) without secondary task. Next, two secondary task tracks followed, one using the acoustic version (AC), and one using the spatial reasoning version (SR) of the secondary task. Finally, the second control track (C2) was completed.

The two secondary task conditions (AC and SR) were presented in counterbalanced order (second or third experimental track). This resulted in two blocks of four experimental tracks (conditions): block 1 and block 2 (see Figure 4). (Actually, there were four blocks, because there were also two orders of administering UFOV and TSA, as explained above, and this distinction was orthogonal to the one between block 1 and block 2.)

Insert Figures 3 and 4 about here

Secondary task stimuli were presented in mono sound to both ears. Each secondary task trial lasted exactly ten seconds. After two city names had been pronounced, a short beep followed (at a fixed interval of 3 s after the beginning of the trial), indicating to the participant that (s)he could start answering the appropriate question about the two cities. It was explained to the participants that they could answer anytime during the trial. The questions were always the same within a condition.

At the beginning of each secondary task condition, the participant received three practice trials without performing the LCT, allowing him (her) to become familiar with the secondary task and to make sure (s)he understood what was required of him/her in this condition.

Fourth, at the end of the experiment, the UFOV was administered for those participants who had received the TSA at the beginning, and the other way around.

Finally, participants were debriefed.

3.4 Design and analysis

3.4.1 Test of Hypothesis 1

A 2×3 analysis of variance was conducted, using SPSS-procedure GLM, and using the LCT-deviation score obtained on each track as dependent variable. The type of secondary task (conditions

C, AC, or SR) was treated as a single within-subjects independent variable, and order of presentation (block 1 or block 2) was the between-subjects variable (conditions C1 and C2 were collapsed into a single condition C). All deviation scores were expressed as the average deviation (averaged across distance intervals) in meters from the normative model (see also Figure 2). The scores obtained for condition SR were predicted to be higher (worse) than those obtained for condition AC. In addition, the deviation scores belonging to condition SR were predicted to be higher than those belonging to condition C. No significant difference was predicted between condition AC and condition C, because of the simple and purely acoustic nature of the secondary task in condition AC.

3.4.2 Test of Hypotheses 2 and 3

It was decided to test Hypotheses 2 and 3 using an overall analysis of variance. To this end, for each track and for each participant four additional LCT-deviation scores were computed: two scores for all steering maneuvers going to the left and two scores for all maneuvers going to the right. Of these, half pertained to the first phase of five seconds and the other half pertained to the last phase of five seconds of each secondary task trial.

Switching maneuvers were defined to start 50 m before passing a switch sign commanding the participant to switch to a different lane. The maneuver was considered ended 50 m after having passed this sign (see Figure 2 for details). Note that the combined switching maneuvers pertained to only part (i.e., 60%) of the overall track length of 3 km.

The distinction between two secondary task trial phases was used in order to have a basis for comparing those trial parts of each secondary task where participants were most actively involved in spatial reasoning or acoustic processing with those parts where they were not so (or less so) involved (necessary for testing Hypothesis 3). Thus, a new independent variable *secondary task phase typicality* was created: a secondary task trial phase was either typical for the type of processing emphasized by the secondary task (acoustic or spatial) or not.

The mappings from secondary task trial phases (first or second) to phase typicality levels (typical or not) were based on a simple cognitive task analysis for the secondary tasks, the outcomes of which are shown schematically in Figure 5. Below, we will summarize the rationale behind these mappings. An informal test of the accuracy of these mappings is described in the next section.

Phase 1 was classified as the typical one under most conditions, because most participants succeeded in answering the secondary task questions within 5 s from the beginning of the trial. This was also observed in a pilot study. In Figure 5, this is indicated by locating all subtasks for most conditions (including the "typical" subtask of acoustic storage in case of condition AC, and that of spatial comparison in case of condition SR) in the first phase of the secondary task.

However, for one condition (SR in block 2: lower-left cells in Figure 5), *phase 2* was classified as the typical one, because here the spatial comparison subtask continued into phase 2, as shown in Figure 5.

This continuation was also observed in the pilot study mentioned above (i.e., answering spatial reasoning questions took, on the average, longer than 5 s, measured from the beginning of the trial, if they belonged to the first secondary task presented to the participants). This was also confirmed by a previous study (Hurts, 2008) in which similar spatial, memory-based questions were used.

In section 4, the pattern of mean LCT-deviation scores observed for each of the cells in Figure 5 is evaluated in order to shed some light on the validity of the mappings and underlying cognitive task analysis. Specifically, it was expected that the longer the chain of subtasks denoted in any Figure 5 cell, the worse the corresponding LCT-deviation score would be (all other things being equal). In section 4, this expectation will be referred to as the "mapping hypothesis".

Insert Figure 5 about here

Hypotheses 2 and 3 were tested using a 2×2×2×2 analysis of variance, with type of secondary task (AC or SR), secondary task phase typicality (typical or not), and switching direction (right-going or left-going) as completely crossed within-subjects independent variables. Order of presentation (block 1 or block 2) served as between-subjects independent variable.

Specifically, *Hypothesis 2* predicted a two-way interaction between switching direction and type of task: for condition SR, LCT-performance would be worse for right-going maneuvers than for left-going maneuvers (simple main effect of switching direction), but for condition AC no such effect was predicted.

Hypothesis 3 predicted a three-way interaction between switching direction, type of secondary task, and phase typicality: the simple main effect described by Hypothesis 2 would be stronger for the typical secondary task trial phases than for the non-typical phases (i.e., a “simple” two-way interaction between switching direction and phase typicality), but for condition AC no such two-way interaction was predicted. The test of both hypotheses depended on the validity of the standard assumptions for analysis of variance. In addition, the test of Hypothesis 3 depended on the validity of the assumption that the transfer from condition AC (if presented first) to condition SR (if presented last), or the other way around, is not asymmetrical.

4. RESULTS

Below, the descriptive statistics and test outcomes pertaining to Hypotheses 1, 2, and 3 will be reported. Because of the exploratory status of the inquiry into the moderating influences of UFOV and TSA, the data relevant to this inquiry will only be addressed in general terms in section *5. Conclusions and Discussion*.

4.1 Descriptive statistics

Table 1 shows means and standard deviations of the LCT-deviation scores and some other variables. The deviation scores are broken down by type of secondary task (C1, C2, AC, or SR). Note that larger deviation scores indicate poorer performance on the LCT.

4.2 Hypothesis 1: distracting effect of type of secondary task

It can be seen in Table 1 that the acoustic version of the secondary task (AC) was, as expected, less distracting in an overall sense (1.63 m deviation) than the spatial reasoning version (SR, 1.73 m deviation). Both secondary task conditions had larger LCT-deviation scores than the control conditions (1.61 m and 1.58 m for conditions C1 and C2, respectively). The 2×3 analysis of variance showed that the overall effect of type of secondary task (AC, SR, or the average of C1 and C2) was statistically significant, $F(2,38) = 13.53$, $p < 0.05$. Post-hoc comparisons revealed that all pair-wise differences between the three conditions were significant ($p < 0.05$), except the difference between condition AC and the average of the two control conditions (no significant difference, $p > 0.10$).

Interestingly, post-hoc analyses also revealed that the net amounts of distraction experienced by each participant for each type of secondary task, were significantly correlated with each other, $r = 0.76$, $p < 0.001$. By the “net amount of distraction”, associated with a secondary task, we refer to the difference between a participant’s average LCT-deviation score belonging to the two control conditions on the one hand, and that same person’s deviation score for the secondary task condition on the other hand. This finding indicates the existence of individual differences in the amount of distraction experienced by people: those participants being distracted more by the acoustic secondary task were also distracted more by the spatial reasoning secondary task, and the other way around. (However, this does not change the fact that the spatial reasoning task was more distracting in an overall sense.)

In summary, Hypothesis 1 was confirmed. The non-significant difference between condition AC and condition C (average of C1 and C2) was considered to be in line with multiple-resources theory (Wickens, 2002) which predicts that the secondary task in condition AC and the LCT require different mental resources (acoustic/verbal and visual/spatial, respectively) and, therefore, will not interfere with each other.

4.3 Hypotheses 2 and 3

Table 2 again shows means and standard deviations of LCT-scores, but this time only for those track segments that corresponded to switching maneuvers. The values are broken down by direction of switching maneuver (left-going or right-going), by type of secondary task (C1, AC or SR), and by secondary task trial phase (first phase or last phase). For the sake of testing Hypothesis 3, the values for condition SR are also broken down by phase typicality (typical or non-typical). (Table 2 does not contain statistics for condition C2.)

Before proceeding to the test outcomes pertaining to Hypotheses 2 and 3, we will first briefly review the empirical evidence for the mapping hypothesis.

4.3.1 Mapping hypothesis

Table 3 shows descriptive statistics based on the same data as in Table 2, but this time for the secondary tasks only and broken down by presentation order (block 1 or block 2), phase typicality (typical or not), and type of secondary task (AC or SR). It can be seen that the mean LCT-deviation scores followed the pattern that was expected on the basis of Figure 5 quite precisely.

We conclude that the way we classified phases as "typical" or "non-typical" on the basis of Figure 5 was supported by the data. Indirectly, these data also support the simple cognitive task analysis on which the Figure 5 mappings were based. Note, however, that we tested the mapping hypothesis only informally and approximately, as was already mentioned in the previous section.

4.3.2 Hypothesis 2: amount of distraction as a function of (in)compatibility between spatial directions currently emphasized in secondary and primary task

In Table 2 it can be seen that right-going maneuvers were, on the average, less accurate than left-going maneuvers. The average deviation scores for these two directions were 2.47 m and 2.09 m, respectively (values not shown in Table 2). The 2×2×2×2 analysis of variance showed that the main effect of direction was significant, $F(1, 18) = 15.32$, $p < 0.01$.

Insert Tables 2 and 3 about here

However, the effect of direction was not statistically different for conditions AC and SR: a non-significant interaction between direction and type of task ($p > 0.10$) was observed.

Surprisingly, the main effect of task was not significant in this analysis, $p > 0.10$ (i.e., condition SR was not more distracting than condition AC in an overall sense), though these two conditions *were* significantly different according to the 2×3 analysis of variance mentioned above. This paradox must be due to the fact that in the 2×2×2×2 analysis the LCT-scores pertained to only 60% of the overall LCT-track length, as was explained above under 3. *Method*. Apparently, when busy performing switching maneuvers, participants are, on the average, not more vulnerable to distraction under condition SR than they are under condition AC.

In summary, Hypothesis 2 was not confirmed. Though right-going switching maneuvers were performed less accurately than left-going maneuvers, this effect turned out to be equally strong for both types of secondary task (for condition AC no effect of direction was expected).

4.3.3 Hypothesis 3: influence on effect described by Hypothesis 2 of secondary task phase typicality

From Table 2 it can also be seen that the amount of distraction was, on the average, larger for the typical phases than for the non-typical phases of the secondary task trials: the average LCT-deviation scores were 2.42 m and 2.15 m for the typical and non-typical phases, respectively (values not shown in Table 2). According to the same 2×2×2×2 analysis of variance, this difference was statistically significant, $F(1, 18) = 70.86$, $p < 0.001$. In addition, it can be seen that the effect of switching direction on amount of distraction was, on the average, larger for the typical phases than for the non-typical phases. The interaction between direction and phase typicality was statistically significant, $F(1, 18) = 11.96$, $p < 0.01$.

Finally, the expected three-way interaction between direction, task, and phase typicality was statistically significant, $F(1, 18) = 52.40$, $p < 0.001$. However, and contrary to expectations, though the direction*phase typicality interaction was in the expected direction for condition SR (see Figure 6), it was in the opposite direction for condition AC (see Figure 7). Specifically, the effect of switching direction (though it went in the same direction as for condition SR) was weaker for the typical phases than for the non-typical phases of condition AC.

Insert Figures 6 and 7 about here

Interestingly, despite the absence of a main effect of type of secondary task (condition SR or AC) on amount of distraction in this analysis (see above under *4.3.2 Hypothesis 2*), closer inspection of the data revealed a significant interaction between type of secondary task and phase typicality, $F(1, 18) = 8.96$, $p < 0.01$. This can also be seen in Table 2: for the typical phases, condition AC was, on the average, more distracting, whereas for the non-typical phases condition SR was more distracting.

Figure 5 and Table 3 suggest an explanation for this finding: the number of subtasks hypothesized for the typical phases was, on the average, larger for condition AC than for condition SR. Therefore, it was to be expected that condition AC was the more distracting one, during these phases. The reverse was true for the non-typical phases.

In summary, Hypothesis 3 was partly confirmed: as expected, the inferiority of right-going switching maneuvers (vis-à-vis left-going switching maneuvers) was larger for the typical phases than for the non-typical phases of the secondary task trials. In addition, this larger effect of switching direction during the typical phases was stronger for condition SR than for condition AC, as was also expected. However, contradicting Hypothesis 3, for condition AC the inferiority of right-going switching maneuvers was also found (but not expected), particularly during the non-typical phases of this condition.

5. CONCLUSIONS AND DISCUSSION

This article reported a laboratory experiment in which a particular type of crosstalk was studied in the context of driver distraction. Specifically, the effect on driving performance was studied of having simultaneous activation in working memory of semantically related spatial codes, these codes being invoked by either a spatial reasoning secondary task or a concurrently performed primary (driving) task. In addition to a spatial reasoning version, an acoustic version of an otherwise identical secondary task was also employed. Driver distraction was measured by means of a standardized tool, called the Lane-Change task.

5.1 Hypothesis 1: distracting effect of type of secondary task

The finding of the present study regarding the distracting effect of spatial reasoning about spoken city names is consistent with a previous study showing the distracting effect of performing an irrelevant mental navigation task while driving (Patrick & Elias, 2009). Both findings lend support to multiple resources theory (Wickens, 2002) and to functional distance theory (Kinsbourne & Hicks, 1978). According to these theories, the more dissimilar two concurrent activities are in a cognitive sense and from the point of view of brain anatomy, the easier it is to time-share these activities.

In section *4.3 Hypotheses 2 and 3*, it was mentioned that when only those parts of the LCT-tracks were analyzed at which switching maneuvers were actually performed (which was done in order to test Hypotheses 2 and 3), the expected main effect of type of secondary task on amount of distraction was not observed. However, additional data analysis revealed that this was only true for individuals with a higher-than-average task-switching ability (as measured by the TSA). In contrast, for participants with a lower-than-average task-switching ability, the expected inferiority of the spatial reasoning secondary task *was* observed. This suggests that high-ability individuals are somehow able to resist being distracted more by the spatial secondary task than by the acoustic secondary task, but only when actually performing switching maneuvers. (The interactions with UFOV-standing did not reveal additional insights, in this regard.)

The finding that the acoustic processing of spoken city names was not distracting vis-à-vis a control condition without secondary task is also consistent with multiple-resources theory: an acoustically oriented task and a (spatially-oriented) driving task can be assumed to require different mental resources, with the result that these tasks can be time-shared relatively easily.

In summary, the present study confirms that a spatial reasoning task, representative of the secondary tasks taking place during real driving, may degrade performance on the primary driving task.

5.2 Hypothesis 2: amount of distraction as a function of the (in)compatibility between spatial directions currently emphasized in secondary and primary task

Though the expected effect of switching direction on LCT-performance was confirmed in this study for the spatial reasoning version of the secondary task, the same effect was also observed for the acoustic version of this task (significant main effect of direction and non-significant task * direction interaction). This suggests that the overall effect of switching direction has little to do with the hypothesized (in)compatibility between spatial directions that are emphasized simultaneously in the primary and secondary task, but must have another explanation.

In a first attempt to identify the conditions under which the overall effect of switching direction is observed, the data of this study belonging to the control conditions C1 and C2 were analyzed. This analysis revealed no significant effect of switching direction, $p > 0.10$.

Second, we re-analyzed the LCT-data collected in a previous experiment (Hurts & Sjardin, 2009), using a visual (rather than auditory) secondary task. This analysis also failed to show evidence for an effect of switching direction.

Third, it is possible that the secondary task instructions had not been understood properly by some participants, with the result that both types of secondary task were performed more or less in the same way. However, this possibility is not very likely, because all participants had received three practice trials on each type of secondary task before they started to perform this task concurrently with the LCT. The experimenter used these trials to make sure the participants had understood his instructions correctly. As another manipulation check, Table 1 shows that secondary task questions under condition SR were not always easy to answer correctly (average accuracy percentage of nearly 80%). In contrast, the questions for condition AC were invariably answered without errors by any participant (no accuracy percentage is shown for condition AC in Table 1).

Fourth, additional data analysis revealed that the expected task * direction interaction *was* observed for participants with a higher-than-average task-switching ability, as measured by the TSA. In contrast, for participants with a lower-than-average task-switching ability, the effect of switching direction was stronger for the acoustic version than for the spatial reasoning version of the secondary task. This may (partly) explain the absence of an overall task * direction interaction. (The interactions with UFOV-standing did not reveal additional insights, in this regard.)

Fifth, in future research the present experiment should be replicated, but with the following simple modification to the spatial secondary task: participants should be asked to state which of the two cities has the most *eastern* (rather than western) orientation. If, as a result of this modification, the effect of switching direction becomes significantly smaller than the one observed in the present study (or even becomes the opposite of it), we can be sure that the effect must be explained in terms of spatial cues in concurrently performed tasks being (in)compatible with each other.

In summary, it is concluded that it was not yet shown convincingly that cardinal spatial cues such as “east” and “west”, appearing in a spatial reasoning task, are subject to crosstalk when egocentric cues such as “left” and “right” appear in a concurrently performed, but unrelated, driving task. However, it was shown that several trivial, alternative explanations for the main effect of switching direction can be ruled out. This issue will be revisited in the next subsection.

5.3 Hypothesis 3: influence on effect described by Hypothesis 2 of secondary task phase typicality

Though the expected two-way interaction between direction and phase typicality and the expected three-way interaction between direction, task, and phase typicality were confirmed, other findings cast doubt on the validity of Hypothesis 3. Specifically, and contrary to expectations, it turned out that right-going maneuvers were not only performed worse than left-going maneuvers during the typical phases of the spatial reasoning secondary task, but also during the non-typical phases of the acoustic secondary task.

This may reflect a phenomenon quite different from the type of cognitive interference and crosstalk on which we have focussed so far. It is known from neurological studies that, when performing spatial tasks, people perform more accurately when processing stimuli originating in the left-hand visual field (Kogure & Hatta, 1999) due to cerebral lateralization. In our study, such a perceptual bias may have caused participants to perform right-going switching maneuvers less accurately than left-going ones. (The interactions with UFOV-standing or TSA-standing did not reveal additional insights, in this regard.)

Furthermore, it can be seen that such a perceptual bias may also explain why the overall effect of switching direction (regardless of phase typicality), that was predicted by Hypothesis 2, turned out to be equally strong for both versions of the secondary task. As was mentioned in 5*.2 Hypothesis 2*, it may be that participants with a lower-than-average task-switching ability are particularly vulnerable to this bias. However, as yet it is unclear why such a bias would particularly affect the non-typical phases of the acoustic secondary task. This also represents an issue for future research.

In summary, this experiment provided evidence for an effect of switching direction (larger LCT-deviations when steering to the right than when steering to the left). Also, this effect seemed to be larger when participants were actually involved in spatial reasoning during a secondary task. Nonetheless, the precise theoretical interpretation of these effects is not clear yet, as a similar effect of switching direction was also observed (but not expected) for those parts of the acoustic secondary task (i.e., all second trial phases) where (probably) no acoustic processing (or any other subtask) was going on.

5.4 Potential applications and recommendations for future research

First, the finding that a realistic spatial reasoning task performed concurrently with the primary driving task may degrade primary task performance also has potential practical implications. Specifically, this finding highlights the importance of carefully designing in-car navigation systems to make sure they impose the least amount of spatial reasoning on the driver as possible. For example, the travel directions that are automatically generated by these systems should not be too complex or require the driver to engage too much in navigational planning while driving, as this may degrade driving performance.

Second, the findings concerning the effects on driver distraction of the (in)compatibility among spatial cues, emphasized by a secondary and a concurrently performed driving task, may also have practical applications, if confirmed in future studies. Obviously, drivers cannot always be prevented from thinking about spatial directions that are irrelevant to the concurrently performed driving task and that may conflict with the direction of specific maneuvers performed as part of this task.

Nonetheless, these findings suggest the importance of the precise *type* and *timing* of spatial reasoning drivers engage in while driving. This knowledge can be used, for example, by designers of in-car navigation systems: when automatically generated travel directions are presented to the driver too early, they may interfere (and cause crosstalk) with the currently performed driving maneuver. The importance of having compatible spatial directional cues can also be seen in the design of display maps in navigation systems: egocentric and (3-D) head-up display maps are generally easier to use for navigation purposes than exocentric (north-up) maps. In other words, physical and mental maps should have similar reference frames (Bryant, & Tversky, 1999).

Finally, the following limitations of this study should be noted. First, though participants were instructed to pay an equal amount of attention to the primary and secondary task, it was not verified whether they actually succeeded in doing so. Nor were the effects on driver distraction tested of alternative attention allocation policies.

Second, in order to test Hypotheses 2 and 3, the overall LCT-track length was broken up in smaller parts corresponding to the precise time periods when participants actually performed switching maneuvers. Though we have not done so, we could also have zoomed in on overall secondary task performance, i.e., measured the accuracy of spatial reasoning performance for only those periods where switching maneuvers were actually performed. In this way, we could have gained additional insights into possible tradeoffs between secondary and primary task performance.

Third and last, though the LCT is a convenient tool for measuring driver distraction in the laboratory, it is not (yet) precisely known to what extent results of behavioural experiments conducted using this tool can safely be generalized to more realistic driving scenarios.

Each of these limitations represents a reason for conducting future studies validating and exploring more deeply the scope and precise interpretation of the present findings. (Other recommendations for future research were given earlier in this section, near the end of *5.2 Hypothesis 2* and *5.3 Hypothesis 3.*)

REFERENCES

Back, M.D., Schmukle, S.C., & Egloff, B. (2005). Measuring Task-Switching Ability in the Implicit Association Test. *Experimental Psychology, 52*(3), 167-179.

Ball, K. & Owsley, C. (1993). The useful field of view test: A new technique for evaluating age-related declines in visual function. *Journal of the American Optometric Association, 64,* 71-79.

Bryant, D. J., & Tversky, B. (1999). Mental representations of perspective and spatial relations from diagram and models. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 25*(1), 137-156.

Carlson, R.A. & Sohn, M.H. (2000). Cognitive control of multistep routines: information processing and conscious intentions. In: S. Monsell & J. Driver (eds.), *Control of cognitive processes. Attention and Performance XVIII,* 443-464. Cambridge, MA: MIT.

Driver, J. & Spence, C. (1998). Attention and the crossmodal construction of space. *Trends in Cognitive Science, 2*(7), 254-262.

Duncan, J. (1979). Divided attention: The whole is more than the sum of its parts. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 216-228.

Elio, R. (1986). Representation of similar well-learned cognitive procedures. *Cognitive Science, 10*(1), 41-73.

Fracker, M. L. & Wickens, C. D. (1989). Resources, confusions, and compatibility in dual axis tracking: Displays, controls, and dynamics. *Journal of Experimental Psychology: Human Perception and Performance, 15*(1), 80-96.

Gordon, C.P. (2009). Crash studies of driver distraction. In: M.A. Regan, J.D. Lee, & K.L. Young (eds.), *Driver distraction: theory, effects, and mitigation.* Boca Raton, FL: CRC Press.

Hirst, W. & Kalmar, D. (1987). Characterizing attentional resources. *Journal of Experimental Psychology: General, 116,* 68–81.

Hommel, B. (1998). Automatic stimulus-response translation in dual-task performance. *Journal of Experimetnal Psychology: Human Perception and Performance, 24*, 1368–1384.

Hurts, K. (2008). Spatial memory as a function of action-based and perception-based similarity. *Proceedings of the 52nd Annual Meeting of Human Factors and Ergonomics Society,* 1165-1169, September, New York.

Hurts, C.M.M. & Sjardin, B. (2009). Driver Distraction, Secondary Visual Task Load, and Attention-Related Abilities. Human Diversity: Design for Life. *Proceedings of 9th International Congress of Physiological Anthropology*, held in Delft, August.

Kinsbourne, M. & Hicks, R. (1978). Functional cerebral space. In: Requin, J. (ed.), *Attention and Performance VII.* Erlbaum, Hillsdale.

Kogure, T. & Hatta, T. (1999). Hemisphere specialization and categorical spatial relations representations. *Laterality, 4*, 321–331.

Kujala, T. (2010). *Capacity, workload and mental contents: exploring the foundations of driver distraction.* Doctoral disseration, University of Jyväskylä, Finland.

Lien, M.C. & Proctor, R.W. (2002). Stimulus-response compatibility and psychological refractory period effects: Implications for response selection. *Psychonomic Bulletin & Review, 9,* 212-238.

Mattes, S. (2003). The lane change task as a tool for driver distraction evaluation. In: H. Strasser, H. Rausch, & H. Bubb (eds.), *Quality of work and products in enterprises of the future.* Stuttgart: Ergonomia Verlag.

Navon, D. (1984). Resources: a theoretical soup stone. *Psychological Review, 91*, 216-234.

Navon, D. (1985). Attention division or attention sharing? In: M.I. Posner & O.S.M. Martin (eds.), *Attention and Performance XI,* 133-146. Hillsdale, NJ: Erlbaum.

Navon, D. & Miller, J. (1987). Role of outcome conflict in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance, 12*, 435-448.

Neale, V.L., Dingus, T.A., Klauer, S.G., Sudweeks, J.D., & Goodman, M.J. (2005). *An Overview of the 100-Car Naturalistic Study and Findings.* Paper 05-0400. National Highway Traffic Safety Administration, Washington, D.C..

Newman, S.D., Keller, T.A., & Just, M.A. (2007). Volitional control of attention and brain activation in dual task performance. *Human Brain Mapping, 28*, 109–117.

Pashler, H.E. & Johnston, J.C. (1998). Attentional limitations in dual-task performance. In: H.E. Pashler (ed.), *Attention,* 155-189. Hove, UK: Psychology Press.

Pashler, H., Johnston, J., & Ruthruff, E. (2001). Attention and performance. *Annual Review of Psychology, 52,* 629–651.

Patrick, R.E. & Elias, L.J. (2009). Navigational conversation impairs concurrent distance judgments. *Accident Analysis and Prevention, 41*, 36–41.

Simon (1990). The effects of an irrelevant directional cue on human information processing. In: R.W. Proctor & G. Reeve, *Stimulus-response compatibility: an integrated perspective*. Amsterdam: North-Holland.

Spence, C. & Driver, J. (2004). *Crossmodal space and crossmodel attention*. Oxford, UK: Oxford University Press.

Spence, C. & Ho, C. (2008). Multisensory interface design for drivers: past, present and future. *Ergonomics, 51*(1), 65–70.

Spence, C. & Read, L. (2003). Speech Shadowing While Driving**:** On the Difficulty of Splitting Attention Between Eye and Ear. *Psychological Science, 14*(3), 251-256.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18,* 643-662.

Wickens, C.D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science*, *3*(2), 159–177.

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Figure 1. Photo showing equipment used for measuring auditory driver distraction using the Lane Change Task.
Note. The small monitor on the left-hand side of the driver was not used in the present experiment.

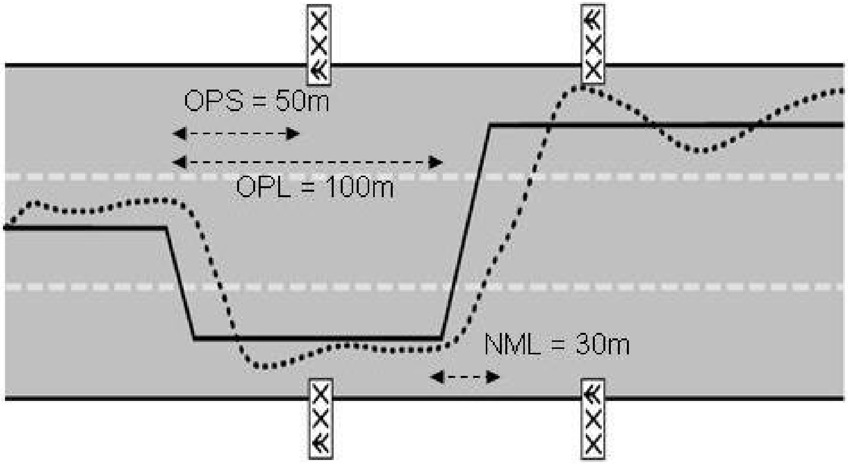
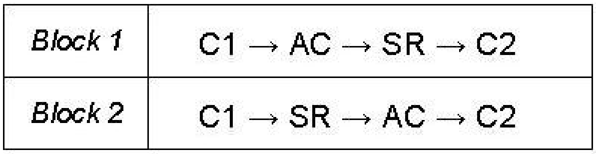


Figure 2. Schematic overview of Lane Change Task.
Note. Car approaches from the left. Solid line represents normative model for switching and driving behavior, dotted line represents actual behavior. Normative length of switching maneuver (called *NML* in figure) set at 30 m. Observation period for each maneuver started 50 m before the appearance of a switch sign (see distance labeled *OPS*) and ended 100 m later (see distance labeled *OPL*). Lane width set at 3.85 m.

......Leeuwarden
......Utrecht
......Sneek
......Breda
......Leiden
......Baarn
......Groningen
......Enschede
......Maastricht
......Den Helder
......Amersfoort
......Vlissingen
......Eindhoven
......Assen
......Scheveningen
......Den Bosch

Figure 3. Empty test map used in short topography training-and-test session.
Note. Participant must fill in numbers of city locations in table at bottom.



Block 1	C1 → AC → SR → C2
Block 2	C1 → SR → AC → C2

Figure 4. Experimental conditions were presented either according to the sequence of block 1, or according to that of block 2.

Note. Meaning of abbreviations: C1 and C2: conditions without secondary task. AC: condition with acoustic version of secondary task. SR: condition with spatial reasoning version of secondary task.

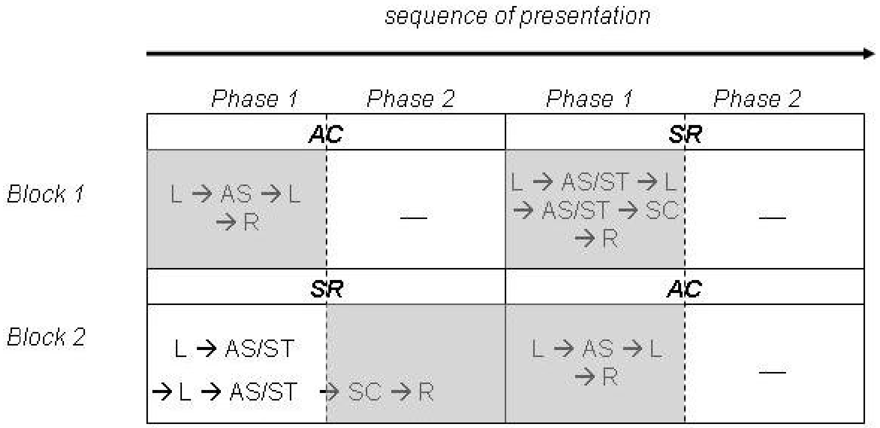


Figure 5. Diagram showing mappings between secondary task trial phases (first or second) and phase typicality levels (typical or non-typical) for each secondary task and for each presentation order (block 1 or block 2).

Note. Meaning of abbreviations: AC = acoustic secondary task; SR = spatial reasoning secondary task; L = listening; AS = acoustic storage; R = response; ST = semantic transformation; SC = spatial comparison. Shaded areas represent typical phases.

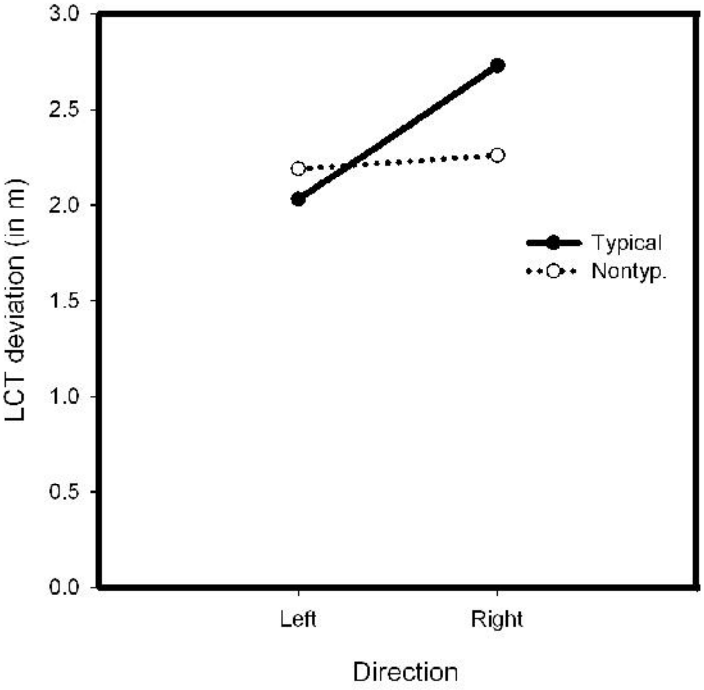


Figure 6. Plot of mean LCT-deviation scores for spatial reasoning (SR) secondary task conditions (switching parts only), broken down by switching direction and secondary task phase typicality (typical or non-typical).

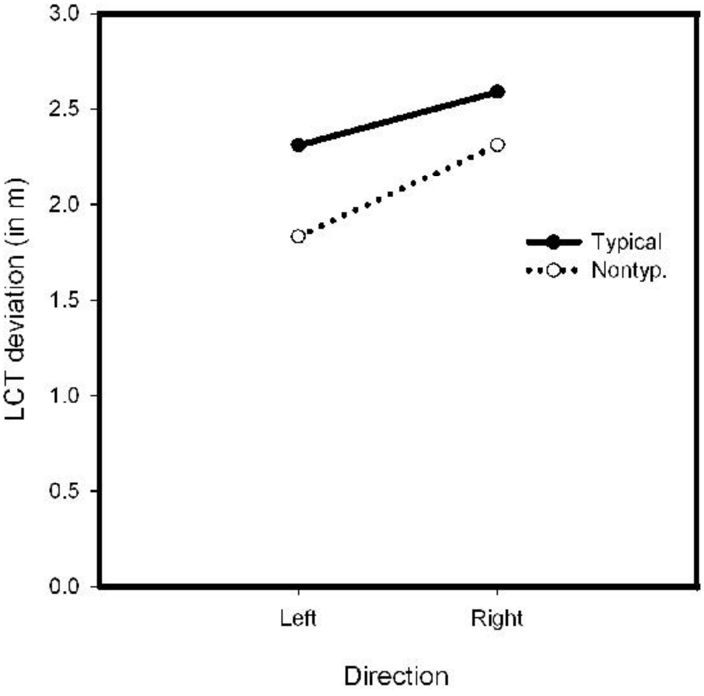


Figure 7. Plot of mean LCT-deviation scores for acoustic (AC) secondary task conditions (switching parts only), broken down by switching direction and secondary task phase typicality (typical or non-typical).

Table 1. Descriptive statistics for LCT-deviation scores (broken down by type of secondary task) and some other (background) variables.

LCT-score	Mean	Standard deviation	Variable	Mean	Standard deviation
C1 (control 1)	1.61	0.23	Driver age (in years)	35.15	16.73
C2 (control 2)	1.58	0.22	Driving experience (cumulative license duration in months)	180.30	190.46
AC (acoustic sec. task)	1.63	0.24	Driving exposure (average number of rides per week)	1.80	0.95
SR (spatial reas. sec. task)	1.73	0.26	Spatial reasoning secondary task performance (% correct)	79.55	10.26

Note. Driving Exposure coded as 1 (for 0 or 1 rides per week), as 2 (for 2 rides per week), or as 3 (for 3 or more rides per week). All numbers based on 20 observations (participants). LCT-scores expressed as average deviations in meters from normative model.

Table 2. Descriptive statistics for LCT-scores (switching parts only), broken down by type of secondary task, switching direction, secondary task trial phase, and secondary task phase typicality.

Type of sec. task	Direction	Phase (typicality)	Mean	Standard Deviation
C1 (control 1)	Left	(Collapsed across phases)	2.35	0.38
	Right	(Collapsed across phases)	2.08	0.23
Acoustic sec. task (AC)	Left	First (typical)	2.31	0.36
		Last (non-typical)	1.83	0.47
	Right	First (typical)	2.59	0.63
		Last (non-typical)	2.31	0.43
Spatial reas. sec. task (SR)	Left	First	2.25	0.39
		Last	1.98	0.48
	Right	First	2.55	0.57
		Last	2.43	0.49
Spatial reas. sec. task (SR)	Left	Typical	2.03	0.45
		Non-typical	2.19	0.46
	Right	Typical	2.73	0.53
		Non-typical	2.26	0.43

Note. The breakdown of condition SR statistics by secondary task trial phase and by phase typicality represent two alternative ways of breaking down the same raw data. All numbers based on 20 observations (participants). Statistics for condition Control 2 excluded.

Table 3. Descriptive statistics for LCT-scores (secondary tasks only, switching parts only), broken down by presentation order, type of secondary task, and secondary task phase typicality.

Presentation order	Phase typicality	Type of sec. task	Mean	Std. deviation
Block 1	Typical	Acoustic (AC)	2.32	0.31
		Spatial reasoning (SR)	2.45	0.39
	Non-typical	Acoustic (AC)	1.98	0.44
		Spatial reasoning (SR)	2.10	0.32
Block 2	Typical	Acoustic (AC)	2.58	0.47
		Spatial reasoning (SR)	2.31	0.36
	Non-typical	Acoustic (AC)	2.15	0.31
		Spatial reasoning (SR)	2.35	0.31

Note. All numbers based on 10 observations (participants).