Investigating the influence of working memory capacity when driving behavior is combined with cognitive load: an LCT study of young novice drivers.

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ABSTRACT

Distracted driving has received increased attention in the literature due to potential adverse safety outcomes. Working memory (WM) capacity supports goal-directedness which minimizes the influence of distracting stimuli in favor of driving-relevant stimuli. Visuospatial and verbal WM capacity can be discriminated and are both addressed during driving. An often posed solution to distracted driving is hands-free technology which should reduce detrimental effects of secondary tasks on driving performance. Interference by distraction can however occur directly at the level of sensory input (e.g., visual) and at the level of WM capacity. Hands-free technology still induces WM load and thereby also leads to decreased driving performance. This study investigated, for young novice drivers (n= 51, age= 17-25), the influence of visuospatial and verbal WM capacity on lane change task (LCT) performance when combined with verbal WM load with increasing complexity (i.e., induced by an auditory-verbal response N-back task). Dependent measures of interest were mean deviation in the lane change path (MDEV), lane change initiation (LCI) and percentage of correct lane changes (PCL). Performance on each measure deteriorated with increasing verbal WM load. Meanwhile, higher WM capacity related to better LCT performance. These relations however differed for visuospatial (MDEV and PCL) and verbal (MDEV and LCI) WM capacity. For PCL, young novice drivers with higher verbal WM capacity were influenced less by the increasing verbal WM load. Based on the current findings it can be concluded that both training WM capacity and limiting distraction can minimize crash risks among young novice drivers.

Keywords: young novice drivers, lane change task, verbal working memory load, visuospatial working memory capacity, verbal working memory capacity
1. INTRODUCTION

Distracted driving has received increasing attention in the literature due to potential adverse safety outcomes. At least 25% of the car crashes in the United States can be related to some form of driver distraction (Stutts et al., 2001; Young & Regan, 2007) and distracted driving is a worldwide problem (Young & Lenné, 2010). As defined by Stutts et al. (2001) “distraction occurs when a driver is delayed in the recognition of information needed to safely accomplish the driving task because some event, activity, object, or person within or outside the vehicle compels or induces the driver to shift attention away from the driving task”. Especially the use of cell-phones and new in-vehicle technologies has created a situation in which driving is often combined with other tasks. Distraction occurs because people are limited in the capacities they can devote to ongoing activities. Therefore, they can only process a limited amount of information before performance deteriorates, which in the case of driving leads to an increased crash risk (Rosenbloom, 2006; Regan et al. Young, 2009; Castro, 2009).

Multiple resource theory states that there are several dimensions of limited resource pools (Wickens, 2002, 2008; Jongen et al., 2011). Examples are, processing stages (i.e., ranging from perception to response selection), modality (i.e., auditory and visual), and type of response (i.e., spatial and verbal). Tasks that address different levels along these dimensions can be executed more efficiently as oppose to tasks that address similar levels.

Working memory (WM) capacity (de Fockert et al., 2001; Buckner, 2004; O’Hearn et al., 2008) allows one to both keep information active in mind and to be able to manipulate it, in order to guide goal-directed behavior. Similar to multiple resource theory (Wickens, 2008), different WM capacity modalities can be distinguished (Baddeley, 1986; Wager & Smith, 2003; Johannsdottir & Herdman, 2010; Koppenol-Gonzalez, Bouwmeester et al., 2012). Visuospatial WM capacity is responsible for processing and storing of visual and spatial information, verbal WM capacity is responsible for processing and storing of auditory and verbal information. Since driving requires processing of both types of information, it also involves both WM capacity subtypes. The goal-directedness of WM capacity minimizes the influence of distracting stimuli in favor of attendance to task-relevant stimuli. Therefore, people with higher WM capacity are less susceptible to interference by distraction (Engle, 2010; Pratt et al., 2011). One often posed solution to alleviate distraction while driving is hands-free technology (e.g., hands-free cell phones). This technology should decrease the impact of secondary tasks on driving since it does not require shifting visual attention away from the roadway, nor does it require manual adjustments of settings (Harbluk et al., 2007; Maciej & Vollrath, 2009) so that they engage different resource dimensions (Wickens, 2008). Interference by distraction can however occur directly at the level of sensory input (e.g., visual) and at the level of WM (also referred to as cognitive) capacity (Recarte & Nunes, 2009; Víctor et al., 2009; Jongen et al., 2011). Hands-free technology thus still induces WM load. When WM capacity resources are depleted by a secondary task, task-irrelevant information interferes more readily and driving performance will deteriorate (Lavie et al., 2004; Blanco et al., 2006; Engström & Markkula, 2007; Reimer et al., 2012). For instance, it has been found that drivers are more likely to miss, or respond slower to, simulated traffic signals while using a hands-free phone (Strayer et al., 2003). As another example, Just et al. (2008) found, using fMRI, that combining driving with language comprehension (i.e., verbal...
WM load) deteriorated driving performance because cognitive resources were occupied by the language task. This effect held even when it did not require holding or dialing the phone (Just et al., 2008).

Although drivers of all ages are affected by distraction, young novice drivers are thought to be especially susceptible (Spronk & Jonkman, 2012). First, the WM capacity of young drivers is limited in comparison to adult drivers. This is due to the fact that the development of WM capacity depends on the maturation of the prefrontal cortex (PFC) and parietal lobes, which start at the age of 11 and last until late adolescence (De Luca & Leventer, 2008). Second, many aspects of driving (e.g., gear shifting) only become automated over time with increasing driving experience. Since non-automated tasks require more WM capacity (Conway et al., 2002) novice drivers need to invest more of their already sparse resources in the driving task (Young & Regan, 2007; Young & Lenné, 2010). Taken together, spare WM capacity resources to execute secondary tasks are limited in young novice drivers. Therefore, when they do perform multiple tasks simultaneously, performance on those tasks is likely to degrade to a greater extent than that of adult drivers (Young & Regan, 2007; Neyens & Boyle, 2007; Underwood, 2007). Finally, despite their limitations, young novice drivers are more willing to accept and use new technologies (Neyens & Boyle, 2007), and also perceive less risk in using potentially distracting technologies (Fofanova & Vollrath, 2011), in comparison to older drivers.

This study included the lane change task (LCT) as an efficient and low-cost driving task that is sensitive to WM load (Engström & Markkula, 2007; Harbluk et al., 2007; ISO, 2010; Fofanova & Vollrath, 2011). For instance, WM load affected an event detection measure in an LCT study from Engström & Markkula (2007). Although WM capacity was already related to LCT performance (Mäntylä et al., 2009), a limited selection of driving parameters (i.e., lateral control) was studied. Furthermore, the interaction between visuospatial/verbal WM capacity and the influence of WM load on LCT performance has not been studied before. This interaction is of interest as it will reflect whether participants with higher WM capacity are less susceptible to increases of WM load. WM load was induced by an auditory-verbal response N-back task that requires both maintenance and manipulation of information in memory (Carte et al., 2003; Mehler et al., 2009; Mehler et al., 2011; Wild-Wall et al., 2011). Three different levels of complexity were included (0-, 1- and 2-back). The auditory-verbal nature of the task allowed verbal WM load to be varied systematically without conflicting with manual control or visual processing. The induced verbal WM load resembles distracting tasks such as hands-free cell phone conversations since they draw on many of the same cognitive resources (i.e., auditory attention and memory) (Mehler et al., 2012). It was expected that for young novice drivers: 1) verbal WM load will impair driving performance; 2) increased visuospatial and verbal WM capacity will be related to superior driving performance; 3) driving performance of participants with higher WM capacity will be less degraded when verbal WM load is increased. Due to the secondary task’s auditory-verbal nature, this was expected to occur especially for higher verbal WM capacity.

2. METHODS

2.1 Participants
A group of 51 young novice drivers (27 females) between 17 and 25 years (mean= 19.42; SD= 1.77) with either a learners permit and minimum 20 hours driving experience (mean months license= 8.38, SD= 5.06), or a permanent license and maximum two years of license possession (mean months license= 11.16, SD= 7.68) participated in the experiment.

2.2 Working Memory Load Task: Auditory-Verbal Response N-back Task

This task was adapted from Mehler et al. (2011). Numeric values ranging from zero to nine were presented to the subject. The time interval between stimuli was 2.25s. The task included three complexity levels which were counterbalanced among participants. The 0-back was low-level; the participant, whilst carrying out the LCT, had to repeat out loud each number immediately after it was presented. For the 1-back, the subject was required to recall and repeat out loud the number that was presented just before the last number they heard, (i.e., one stimulus back). For the 2-back, participants were required to recall and repeat out loud the number that was presented two numbers before the last number they heard. This task followed the stages from multiple resource theory (Wickens, 2002). It first required the investment of WM capacity resources in an auditory processing and perception stage after which the information needed to be held in memory. Participants needed to maintain the numbers in mind while updating the order in which the numbers were meant to be reproduced. Finally, WM capacity resources needed to be invested in the selection and execution of a verbal response. These auditory attention and memory components draw on many of the same cognitive resources as technology with an auditory-verbal nature, for instance hands-free cell-phones (Manoach, 2003; Mehler et al. 2012).

2.3 Working Memory Capacity Tasks (Fig. 1)

Visuospatial WM capacity: Visuospatial Span

In this task, a 4-by-4 grid was presented on screen and a number of squares in the grid would sequentially and randomly turn blue. Participants were instructed to reproduce the sequence in the correct order by clicking on the squares that had changed color by use of a computer mouse. Initially, the task involved a sequence of three items. When participants correctly reproduced the sequences on two consecutive trials, one item was added to the sequence on the next trial. When participants were not able to correctly reproduce sequences on two consecutive trials, the task stopped (Houben et al., 2011).

Verbal WM capacity: Letter Span

In this task, a series of letters was sequentially presented on screen with each letter being connected to a central circle. After presentation of the complete letter set, participants needed to indicate which letter appeared at the location now presented in red (i.e., indicated with an arrow in Fig. 1). The task started with a sequence of three items. When participants correctly reproduced the sequences on two consecutive trials, one item was added to the sequence on the next trial. When participants were not able to correctly reproduce sequences on two consecutive trials, the task stopped (Houben et al., 2011).
2.4 Lane Change Task (LCT)

The LCT Sim v1.2, developed by Daimler AG, consisted of three-km road tracks with 18 lane change signs. Participants were instructed to perform lane-change maneuvers in the direction indicated by the sign (Fig. 2), while maintaining a constant speed of 60 km/hour. Participants were instructed to change lanes as soon as the information on the sign was visible. This change should be deliberate, abrupt and efficient, with the change executed before the sign. Mean distance between signs was 150m, resulting in a mean duration of nine seconds between lane changes. One track can be completed in approximately 180 seconds (Mattes, 2003). Participants used a force-feedback steering wheel to control the simulation. Meanwhile, simulated vehicle engine sounds made the driving situation more realistic. The LCT consisted of six tracks: tracks one and two were training tracks to familiarize subjects with the task and did not include WM load; the third track served as a baseline measurement (i.e., without WM load); tracks four to six were combined with one of the three auditory-verbal N-back tasks. Every participant first completed tracks one to three, tracks four to six were counterbalanced among participants.

2.5 Procedure

Upon arrival, participant signed an informed consent. The verbal WM load was trained starting from simple to complex. More specifically, they practiced one sequence of the 0-back, two sequences of the 1-back and three sequences of the 2-back. A limited amount of additional practice sequences were allowed when performance was below the minimum proficiency level (see Mehler et al. (2011) for more information). The subject then performed six LCT tracks. Participants might be tempted to adopt a compensatory strategy where they mainly focus on the N-back task during straight segments, therefore they were asked to not prioritize a task but perform as well as possible on both (Rydström et al., 2009). Participants then completed both WM capacity tasks starting with the visuospatial span and following with the letter span.
3. DATA ANALYSIS

3.1 Working Memory Load Task: Auditory-Verbal Response N-back Task

For each level of the verbal WM load, the percentage of incorrect responses was used as an error rate.

3.2 Working Memory Capacity Tasks

For the visuospatial and verbal WM capacity tasks, the number of items in the sequence that could be correctly reproduced (i.e., the level that was reached) was used as the outcome measure, with a higher level indicating a better WM capacity (Houben et al., 2011).

3.3 Lane Change Task (LCT)

Dependent measures, known to be influenced by WM load, were derived from existing literature (Engström & Markkula, 2007; ISO, 2010; Young et al., 2011).

- Mean deviation in lane change path (MDEV): deviation between the position of the normative model and the actual driven course (Fig. 3). The normative model was an adaptive model based on the baseline level of the participant which makes it (Petzoldt et al., 2011). This measure covers at least three aspects of LCT performance that all can explain an increased deviation: perception (i.e., late perception of the sign or missing a sign), maneuvering quality (i.e., slow lane changes) and lane keeping quality.

- Event detection measures:
  - Lane change initiation (LCI): the start of the initiation was defined as the first instant that the steering wheel angle was greater than, or equal to, 3 degrees when required to move by one lane position; or 6 degrees when required to move by two lane positions. A steering event was only recorded if the driver steered in the proper direction. The distance travelled from the beginning of the segment, when the road sign appears, to the initiation was computed for each of the 18 segments and averaged. This measure assesses merely event detection although it also covers processes of response selection and preparation (i.e. selection of the target lane and preparation of the lane change).
  - Percentage of correct lane changes (PCL): the number of correct lane changes that occurred until 40m after the sign was assessed (i.e., cases where signs were missed or incorrectly responded to were identified) and divided by the total of 18 required changes to calculate the percentage of correct lane changes. In terms of information processing stages this measure reflects stages ranging from detection of the sign, response selection and preparation, to the actual response execution (i.e., the correct lane change).
4. DATA ANALYSES

Exploratory analyses were conducted to identify outliers (± 3 standard deviations from the mean) per verbal WM load level, and per dependent measure, in order to be removed from relevant analyses. To verify the manipulation of WM load (i.e., more N-back task errors with increasing complexity), a repeated measures analysis of variance (ANOVA) on the N-back task was conducted with load (3: 0-, 1- and 2-back) as a within subject factor. Repeated measures analyses of covariance ANCOVA with load (4: baseline, 0-, 1- and 2-back) as a within subject factor and WM capacity as a covariate were conducted to assess: 1) if WM load had detrimental effects on LCT driving behavior (main effect verbal WM load); 2) if WM capacity was positively related to LCT driving behavior (main effect visuospatial/verbal WM capacity); 3) if the effect of verbal WM load on driving behavior was dependent on WM capacity (interaction effect WM load * visuospatial/verbal WM capacity). Separate models were analyzed per dependent measure.

5. RESULTS

**TABLE 1 descriptive statistics (n = 51)**

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDEVb</td>
<td>.44</td>
<td>.41</td>
<td>.15</td>
<td>.21</td>
<td>.85</td>
</tr>
<tr>
<td>MDEV0</td>
<td>.46</td>
<td>.44</td>
<td>.14</td>
<td>.22</td>
<td>.78</td>
</tr>
<tr>
<td>MDEV1</td>
<td>.62</td>
<td>.52</td>
<td>.29</td>
<td>.25</td>
<td>1.81</td>
</tr>
<tr>
<td>MDEV2</td>
<td>.74</td>
<td>.65</td>
<td>.30</td>
<td>.25</td>
<td>1.49</td>
</tr>
<tr>
<td>LCIb</td>
<td>10.51</td>
<td>10.22</td>
<td>1.36</td>
<td>8.44</td>
<td>15.13</td>
</tr>
<tr>
<td>LCI0</td>
<td>11.41</td>
<td>11.24</td>
<td>1.33</td>
<td>9.31</td>
<td>14.80</td>
</tr>
<tr>
<td>LCI1</td>
<td>12.93</td>
<td>12.60</td>
<td>2.24</td>
<td>8.79</td>
<td>18.19</td>
</tr>
<tr>
<td>LCI2</td>
<td>13.71</td>
<td>12.86</td>
<td>2.41</td>
<td>9.78</td>
<td>19.91</td>
</tr>
<tr>
<td>PCLb</td>
<td>98.91</td>
<td>100</td>
<td>2.94</td>
<td>88.89</td>
<td>100</td>
</tr>
<tr>
<td>PCL0</td>
<td>98.91</td>
<td>100</td>
<td>3.52</td>
<td>77.78</td>
<td>100</td>
</tr>
<tr>
<td>PCL1</td>
<td>96.51</td>
<td>100</td>
<td>5.33</td>
<td>72.72</td>
<td>100</td>
</tr>
<tr>
<td>PLC2</td>
<td>94.33</td>
<td>94.44</td>
<td>6.80</td>
<td>72.22</td>
<td>100</td>
</tr>
</tbody>
</table>
5.1 Working Memory Load Manipulation

As expected, the increasing verbal WM load was effective, with more errors being made in more difficult levels (F(2,86)= 147.2, p<.0005).

5.2 Working Memory Load And Working Memory Capacity Effects

### TABLE 2 Statistical values

<table>
<thead>
<tr>
<th>LCT measure</th>
<th>Verbal WM load X visuospatial WM capacity</th>
<th>Verbal WM load X verbal WM capacity</th>
<th>WM load X visuospatial WM capacity</th>
<th>WM load X verbal WM capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDEV</td>
<td><strong>F(3,141)= 51.3, p&lt;.0005</strong></td>
<td>*F(1,47)= 4.4, p=.041, r= -.454</td>
<td>*F(1,47)= 5.5, p=.024, r= -.472</td>
<td>F(3,411)= .292, p=.759</td>
</tr>
<tr>
<td></td>
<td><strong>F(3,144)= 78.77, p=.000</strong></td>
<td>F(1,48)= .006, p=.94, r=.201</td>
<td>*F(1,48)= 4.84, p=.033, r=.358</td>
<td>F(3,144)= .19, p=.854</td>
</tr>
<tr>
<td></td>
<td><strong>F(3,114)= 22.5, p&lt;.0005</strong></td>
<td>*F(1,38)= 5.3, p=.027, r= .464</td>
<td>F(1,38)= 1.625, p=.208, r=.373</td>
<td>F(3,114)= .47, p=.017</td>
</tr>
<tr>
<td>PCL</td>
<td><strong>F(3,51)=11.504, p=.000, η²=.404, mean differences: .926-3.396-7.409</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCL (low verbal WM capacity)</td>
<td><strong>F(3,66)=10.301, p=.000, η²=.319, mean differences: .0-1.45-2.9</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*p<.05 (one-tailed); **p<.01 (one-tailed)

See Table 2 for the statistical values.
MDEV. MDEV degraded with increasing verbal WM load. Participants with higher visuospatial WM capacity and higher verbal WM capacity showed less deviation from the adaptive path. There was no interaction of WM load with either of the WM capacity measures. However, the interaction between verbal WM capacity and the effect of verbal WM load on MDEV did show the expected pattern (i.e., less influence for participants with higher verbal WM capacity, see Figure 4).

LCI. Lane changes were initiated more slowly with increasing verbal WM load. Participants with higher verbal WM capacity displayed lower LCI values, whereas there was no main effect of visuospatial WM capacity. There was no interaction effect of verbal WM load with either of the WM capacity measures. Again, the interaction between verbal WM capacity and the effect of verbal WM load on LCI did show the expected pattern (i.e., less influence for participants with higher verbal WM capacity, see Figure 5).

PCL. Less correct lane changes were made with increasing verbal WM load. Participants with higher visuospatial WM capacity made more correct lane changes, whereas there was no main effect of verbal WM capacity. There was no interaction effect of WM load with visuospatial WM capacity. There was an interaction of verbal WM load and verbal WM capacity. To further investigate this interaction effect, a median split was conducted on verbal WM capacity that allowed separate analyses for participants with a low and high verbal WM capacity (see Figure 6). In both the low and the high verbal WM capacity group, less correct lane changes were made with increasing WM load. The effect however was larger for the low verbal WM capacity group indicating a larger degradation of performance with increasing WM load.

In sum, an increase of verbal WM load led to degraded LCT performance for all the dependent measures (MDEV, LCI and PCL). Participants with higher visuospatial WM capacity showed less deviation from the adaptive model (MDEV) and made more correct lane changes (PCL). Participant with higher verbal WM capacity showed less deviation from the adaptive model (MDEV) and initiated their lane changes faster (LCI). Finally, with increasing verbal WM load, the decrease of correct lane changes was smaller for participants with higher verbal WM capacity.

FIGURE 4 Interaction between verbal WM capacity and verbal WM load for MDEV
The goal of this research was to investigate, for young novice drivers, the influence of WM capacity when LCT performance was combined with verbal WM load. While previous studies already established degrading effects of WM load on driving performance (Blanco et al., 2006; Harbluk et al., 2007; Reimer et al., 2012), they did not investigate the effect of WM capacity. Therefore, this study sought to determine if higher WM capacity was related to better LCT performance. Furthermore, it determined if performance deterioration, due to increasing verbal WM load, was smaller with higher WM capacity. Due to the verbal nature of WM load it could be expected that mainly verbal WM capacity would be addressed to deal with the increasing load.

The results replicated and extended previous LCT findings where distraction, induced by WM load, affected the adaptive model (Harbluk et al., 2007), as well as event detection (Engström & Markkula, 2007). The verbal WM load reduced available WM capacity
resources and LCT performance degraded for the selected measures (i.e., MDEV, LCI and PCL). The adaptive model (MDEV) is a measure of overall LCT performance. This summary measure is influenced by the detection and response to road signs as well as maintaining lateral positioning (Trbovich, 2007). The current MDEV result extends earlier results in which the LCT was combined with WM load as induced by an N-back task. Lei & Roetting (2011) however used a visual N-back task (i.e., three levels: baseline, 1- and 2-back that induced visual WM load. The current verbal WM load manipulation did not address visual resources. Nonetheless, overall LCT performance as measured by MDEV declined. Therefore, and in agreement with other research, hands-free technology is not a solution to reduce by distraction caused decrements in overall LCT performance (Harbluk et al., 2007). Separate information processing components can be discriminated in MDEV. From these, two event detection measures were found to be especially susceptible to WM load, LCI and PCL (Harbluk et al., 2007; Engström & Markkula, 2007). These measures represent different information processing stages, ranging from detection to response selection and preparation and from detection to response execution (ISO, 2010). As explained in the method section, the additional component of PCL (vs. LCI) is response execution which occurs after the preparation of the lane change. The separation of both measures is supported in as study which showed that motor programming does not always necessitate response execution (Osman et al., 1990). Further support comes from an eye tracking study that evaluated the time course of a lane change. In this, the primary visual focus of the driver shifted from the starting lane to the target lane only after the onset, or in this case the preparation, of the lane change (Salvucci & Liu, 2002). The current results showed that verbal WM load had a detrimental effect on both event detection measures. This is in line with other LCT, simulator and on-road studies, where WM load deteriorated performance on measures of detection and response (Lamble et al., 1999; Harbluk et al., 2007; Lee et al., 2007). For instance, WM load that was induced by an auditory-verbal task delayed responses to a pedestrian detection task (Lee et al., 2009). A further breakdown of event detection measures beyond LCI and PCL (e.g., sign detection, target lane selection) was not possible with the current methodology. As for LCI, Recarte & Nunes (2003) found with the use of eye-tracking that WM load, induced by an auditory-verbal task, mainly impaired visual detection on a cognitive task due to late detection and poor identification rather than response selection. Nonetheless, the study included a simple task, with a limited two-alternative choice, which could have caused the non-existing effect on response selection. Another possibility to decompose measures of event detection is the inclusion of electroencephalography (EEG). This technique indicates the precise timing of cortical processing with the use of event related potentials (ERP’s) (Pratt et al., 2011). For instance, the occurrence of a lateralized readiness potential (LRP) indicates the selection of an appropriate response (Luck, 2012). To summarize, WM load degraded overall LCT performance as well as detection, response selection, preparation and execution. Activities that are distracting to the driving task, such as cell phone conversations or interacting with auditory in-vehicle devices, imply similar auditory attention and memory components as the current verbal WM load (Mehler et al., 2012). Therefore, these tasks will likely cause comparable degrading effects on driving. Indeed, in an LCT study, Treffner & Barrett (2004) found that the use of a hands-free phone negatively influenced the sensitivity to prospective information about upcoming events during a braking task executed at a closed-circuit driving track environment.
As for WM capacity, the current study was the first to show that participants with high WM capacity display a better performance on measures of event detection. This extends on previous research that related better MDEV performance with increased WM capacity (Mäntylä et al., 2009). The inclusion of visuospatial as well as verbal WM capacity allowed detailed inferences about the relation between WM capacity and LCT performance. Participants with higher visuospatial WM capacity performed better on MDEV and PCL while participants with higher verbal WM capacity performed better on MDEV and LCI. As stated above, MDEV is a summary measure which does not only include path control, both also detection and response measures (ISO, 2010). This generality of the driving measure probably caused the relation with both visuospatial and verbal WM capacity. For instance, this measure depends on visual inputs to determine lane positioning as well as on the interpretation of the signs to correctly change lanes. When considering the event detection measures, even though LCI and PCL both depend on the correct interpretation of information displayed on the sign, they related independently to WM capacity. LCI related to verbal WM capacity while PCL related to visuospatial WM capacity. This shows that visuospatial activity depends on different resources than verbal activity. Furthermore, both measures addressed different processing stages ranging from detection and response preparation (i.e., LCI) to detection and response execution (i.e., PCL). These findings are in line with multiple resources theory (Wickens, 2008). As for the relation between verbal WM capacity and LCI, a distinction can be made between object (e.g., a traffic sign or lane change sign) visual WM capacity and visuospatial WM capacity. In contrast to visuospatial WM capacity, object WM capacity depends on verbal mediation (Postle et al., 2005; Postle & Hamidi, 2007). For instance, in comparison to the performance on visuospatial N-back WM capacity task, performance on an object WM capacity task was found to be more sensitive to verbal distraction (i.e., word judgment task). Just as word stimuli are encoded not only by their semantic and lexical information, but also by non-linguistic and contextual information, memory for objects includes a semantic component. More specifically, a semantic code contributes to the retention of object identity which is an extension to the multiple encoding model (Wickens, 1976). Therefore, the relation between verbal WM capacity and LCI could have been caused by the multiple encoding of objects. The selection of the target lane depended on the contribution of a semantic code to the retention of the lane change sign. Lastly, participants needed to correctly execute the lane change (PCL) and this measure related strongly to visuospatial WM capacity. Visuospatial WM capacity was already linked to the execution of movement in the immediate environment (Garden et al., 2002). To change lanes it is necessary to selectively control attention. More specifically, attention needs to be directed to a new location in the visual field (i.e., target lane) while performing the WM load task. Such voluntary shifts of attention have been postulated before to engage WM capacity (Awh et al., 1998; Rosen, et al., 1999; Downing, 2000; Redick & Engle, 2006; Zimmer, 2008; Ross, et al., in submission). To summarize, the finding that WM capacity related to overall LCT performance as measured by MDEV was extended by the inclusion of LCI and PCL as well as the inclusion of visuospatial and verbal WM capacity measures. Participants with higher visuospatial WM capacity showed less deviation from the adaptive model (MDEV) and made more correct lane changes (PCL). Participants with higher verbal WM capacity showed less deviation from the adaptive model (MDEV) and initiated their lane changes faster (LCI).
Importantly, this study was the first to find that the relation between WM load and LCT performance was moderated by WM capacity as it influenced the strength of it. This is in line with findings that WM capacity predicts performance on a range of cognitive and real-world tasks (Engle, 2002) and that it allows the prioritization of attendance to task-relevant stimuli (de Fockert et al., 2001; Pratt et al., 2011). Young novice drivers with higher WM capacity were influenced less by increasing WM load, as reflected by a smaller decrease of correct lane changes in people with high (versus low) verbal WM capacity when load increased. This coincides with theories and findings that the availability of extra WM capacity leaves room for greater abilities to employ attention to avoid distraction (de Fockert et al., 2001; Engle, 2002; Pratt et al., 2011). As hypothesized, this result was only found for verbal WM capacity (Johannsdottir & Herdman, 2010; Koppenol-Gonzalez et al., 2012). The verbal WM load required verbal WM capacity in order to process the auditory digits, and to respond verbally. Therefore, participants with higher verbal WM capacity possessed spare resources to deal with the increasing complexity of the verbal WM load. The moderating influence of verbal WM capacity was only significant for correct lane changing (PCL). Even though the pattern was present, performance on the adaptive model (MDEV) and the initiation of lane changes (LCI) was not significantly alleviated by higher verbal WM capacity. PCL is the only measure that isolates the actual correct execution of the lane change (see discussion PCL in previous paragraph). WM capacity allows participants to be goal-directed (Buckner 2004). In this case the goal is to change to the correct lane change. At the same time, information from conflicting lanes can interfere more readily when lane changing is combined with verbal WM load (Lavie et al., 2004). This interference can lead to response conflicts (e.g., choose the left lane next to the current lane or the left outer lane). Resolving response conflict resolution is known to rely on WM capacity in that people with higher WM capacity are better in conflict resolution (Kane & Engle, 2003). This could explain why participants with higher verbal WM capacity were less influenced by the increasing verbal WM load. They are less likely to select the wrong lane due to goal-irrelevant information (e.g., competing information from the outer left lane). Effects of WM capacity on selective attention in situations of conflict have been shown before (de Fockert & Bremner, 2011). Since conflict resolution is time consuming (Hommel, 2000), the duration of the lane changes could be included as an additional measure to determine whether such response conflicts actually occur. When translating these LCT findings to real car driving, an example of this interaction can be seen on highways. While driving on a highway, people not only need to process information concerning their own vehicle (e.g., lateral lane keeping) and other drivers (e.g., braking of a lead vehicle), people also need to be aware when and where to exit the highway. The current results indicate that while participants with higher verbal WM capacity might be faster to initiate the change to the exit lane (i.e., early detection, response selection and response preparation), they still become slower when induced by verbal WM load (e.g., listening to music, hands-free phone use). However, even though they are slower in the first stages of lane changing, the execution of their lane change is less affected by the increasing WM load and they will be less likely to choose the wrong exit. It would be interesting for future research to determine whether this effect exists for the influence of visuospatial WM capacity on LCT performance combined with visuospatial WM load. Changing to the correct lane appeared to be the only LCT performance measure where participants with higher verbal WM capacity were negatively less influenced by increasing verbal WM load. Meanwhile, conflict resolution has been proposed as the underlying mechanism.
7. LIMITATIONS

Questions could be raised concerning the transfer of LCT performance to real-life driving. The LCT only requires lane changes over a constant time period; no other driving conditions are included. Furthermore, the instruction to change lanes in a deliberate manner may not resemble daily driving conditions. However, the LCT has been proven a valid way for measuring distraction effects (Engström & Markkula, 2007; Harbluk et al., 2007). Furthermore, the lane keeping and detection measures do resemble necessary functions for real-life driving. Nonetheless, further research should be able to address additional driving parameters in order to gain a more complete image of the above described relations between WM capacity and driving performance. Driving simulator, or on-road driving, studies could allow investigation of other driving parameters which cannot be investigated with the LCT. For instance, it would be interesting to investigate if other driving parameters that withhold response execution, such as reacting to slowing vehicles, would show the same interaction with verbal WM capacity when loaded with auditory-verbal WM capacity tasks. A possible question could be if people with a high verbal WM capacity collide less with slow vehicles in a driving simulation?

8. RECOMMENDATIONS

The found relationship between WM capacity and driving performance, as measured by an LCT, allows some possible applications. First, training WM capacity might lead to an overall better driving performance. Indeed, training WM capacity with a visuospatial N-back task already improved simulated driving performance in older adults (Cassavaugh & Kramer, 2009). Training might even, at least for some driving parameters, lead to superior coping with distraction by diverting attention away from distracting activities. This could compensate the before mentioned causes that make young novice drivers susceptible to distraction (e.g., low level of driving experience). Second, WM capacity measures could be used to screen young novice drivers for the necessity to include WM capacity training in driver learning programs. For instance, include a mandatory screening in the graduated driver licensing (GDL) system which already withholds several restrictions for adolescents that are learning how to drive (e.g., limiting nighttime driving and transport of passengers) (Masten et al., 2011). More research however will be necessary to determine what kind of WM capacity training/screening might alleviate effects of distraction on driving. As showed in this study, the appropriate type (e.g., visuospatial vs. verbal) will also depend on the driving parameter of interest.

Nonetheless, the degrading effect of distraction by verbal WM load in this study for both high and low WM capacity participants clearly indicates the need to try to eliminate distraction as much as possible. This holds especially for young novice drivers as they are more susceptible to distraction related crashes and are more willing to accept risks accompanying potentially distracting technology (Neyens & Boyle, 2007). One option is to use technologies to either detect distraction or to prevent distraction (Lerner et al., 2010). For instance, the Key2SafeDriving device is a cell phone blocker that transmits a disabling signal.
to a selected cell phone. Incoming calls are directly send to voicemail. Emergency calls however will never be disabled (NHTSA, 2010). Shabeer & Wahidabanu (2012) describe a system that detects the use of a mobile phone and notifies the nearest police post who can take legal actions. Another option to target distraction is education. It is for instance necessary to raise awareness since most drivers are clueless of the extent to which distractions induced by WM load deteriorate driving performance (Council, 2010; Šmolíková et al., 2012). An example of an educational training program for young novice drivers targets risks and distractions from passengers by teaching communication skills to both parties (Lenné et al., 2011).

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