# Does working memory capacity offer protection to driving performance when working memory load increases?

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Number of words = 5537

Number of Figures = 4

Number of Tables = 0

Number of words incl. Figures and Tables = 6537

Paper submitted: 1st of August, 2012
Revision submitted: 15th of November

**ABSTRACT**

Distracted driving has received increased attention in the literature due to potential adverse safety outcomes. Goal-directness, which is related to working memory (WM) capacity, might alleviate influence by distraction. WM capacity consists of different subtypes that are both addressed during driving, visuospatial and verbal WM. An often posed solution to distracted driving is hands-free technology which should reduce detrimental effects of secondary tasks on driving performance. However, because interference by distraction also occurs at the WM level, hands-free technology still induces WM load which could cause decrements in driving performance. This study investigated the influence of visuospatial and/or verbal WM capacity on distracted driving for young novice drivers (n= 51, age= 17-25). Driving performance was measured by a lane change task (LCT) under baseline conditions as well as in combination with three levels of increasing verbal WM load (i.e., induced by an auditory-verbal response N-back). Dependent measures of interest were mean deviation in the lane change path (MDEV), lane change initiation (LCI) and percentage of correct lane changes (PCL). Results showed that performance on each measure deteriorated with increasing distraction. Furthermore, higher WM capacity was related to better LCT performance, although this relation differed per WM capacity measure. Finally, for PCL, young novice drivers with a high verbal WM were less influenced by distraction. Together, these results suggest that a combination of WM capacity training and discarding distraction as much as possible might be the best solution for minimizing crash risks.

## 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 *(1,2)* and distracted driving is a worldwide problem *(3)*. 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." *(1)*. 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 then leads to an increased crash risk *(4,5,6)*. A possible moderator for dual-task performance is working memory (WM) capacity *(7,8,9)*. WM capacity allows one to both keep information active in mind and being able to manipulate it, in order to guide goal-directed behavior. This goal-directedness minimizes the influence of distracting stimuli in favor of attendance to task-relevant stimuli. When WM resources are depleted by a secondary task, task-irrelevant information interferes more readily with the primary task and performance deteriorates *(10)*. It can be expected, and has been shown before, that people with higher WM capacity are less susceptible to interference by distraction *(11)*. Different subsystems of WM capacity can be distinguished, visuospatial and verbal WM *(12,13,14)*. Visuospatial WM is responsible for processing and storing of visual and spatial information, verbal WM is responsible for processing and storing of auditory and verbal information. Since driving requires processing of both types of information, it probably also requires both WM subtypes.

Although drivers of all ages are thought to be affected by distraction, young novice drivers are thought to be especially susceptible. Many aspects of driving become automated over time with increasing driving experience. As automated tasks require less WM capacity *(15)*, this automatization allows the driver to execute the driving task while devoting minimal attention to basic maneuvers such as gear shifting. Novice drivers, however, have low experience levels and therefore driving is not automated in the same way as it is for experienced drivers. As a result they need to investigate more resources in the driving task itself and have less spare capacity to devote to secondary tasks *(2,3)*. Importantly, the WM capacity of young drivers is limited in comparison to adult drivers since WM capacity only begins to take on adult forms in late adolescence. 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 *(16)*. Resulting from lower driving experience, and their developing WM capacity, young novice drivers lack spare WM resources to devote to secondary tasks. When they do perform multiple tasks simultaneously, performance on those tasks is likely to degrade to a greater extent than that of adult drivers *(2,17,18,19)*. For instance, text messaging during driving causes a detrimental effect on several critical driving measures *(20)*. Lastly, despite their limitations, they are more willing to accept and use new technologies, in comparison with older drivers *(17)*, and also perceive less risk in using such technologies *(21)*.

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 *(22,23)*. Interference by distraction can however occur directly at the sensory input level (e.g., visual) but also at the WM (also referred to as cognitive) level *(24,25)*. Hands-free technology still induces WM load and it has been shown that engaging in such activities disrupt driving performance *(26,27,28,29,30)*. 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 *(31)*. As another example, Just et al. (2008) found, using fMRI, that combining language comprehension (i.e., verbal

WM load) and driving decayed 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 *(32)*.

This study employed the lane change task (LCT) as an efficient and low-cost driving performance measure. The LCT allowed for a selection of dependent measures already postulated to be influenced by WM load *(29,33,34,21)*. For instance, WM load affected detection and response selection measures in a LCT study from Engström & Markkula (2007) *(29)*. In the current study WM load was induced by an N-back task that requires one to both maintain and manipulate information in memory *(35,36,37,38)*. More specifically, this study entailed an auditory-verbal response N-back, which induces verbal WM load and resembles distracting tasks such as hands-free cell phone conversations since they draw on many of the same cognitive resources *(39)*. Although WM capacity was already related to LCT performance *(40)*, a limited selection of driving parameters was studied. Furthermore, the interaction between visuospatial/verbal WM 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 verbal WM load. Hypotheses of this study included: 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 high WM capacity will be less degraded when verbal WM load is increased. Due to the secondary task's auditory-verbal nature, especially higher verbal WM will become more important when WM load is increased.

## METHODS

### 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).

### 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. 1), while maintaining a constant speed of 60 km/hour. 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 *(41)*. 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. The first two were training tracks to enable the subject to familiarize with the task and did not include WM load. The third served as a baseline (i.e., without WM load) measurement. Tracks four to six were combined with the auditory-verbal N-back increasing complexity. The three LCT-N-back combinations were counterbalanced among participants.

**FIGURE 1 Simulated three-lane road**

**Auditory-Verbal Response N-back**

This task was adapted from Mehler et al. (2011) *(38)*. 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. The auditory-verbal nature of the task allowed WM load to be systematically varied without conflicting with manual control or visual processing of the LCT *(36)*.

**Working Memory Capacity Tasks (Fig. 2)**

*Visuospatial WM capacity: Visuospatial Span*

In this task, a 4-by-4 grid was presented on screen and a certain 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 *(42)*.

*Verbal WM capacity: Letter Span*

In this task, a series of letters was sequentially presented on screen in a circular manner. Together with each letter an arm lighted up that was connected with a central circle. After presentation of the complete letter set, one of the arms from this circle was presented in red and participants had to use the keyboard to indicate which letter was previously connected to this arm. Task sequence was the same as for the previous WM capacity task *(42)*.

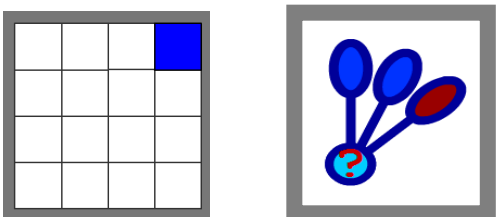

**FIGURE 2 Visuospatial and letter span**

**Procedure**

Upon arrival, participant signed an informed consent. The verbal WM load was trained starting from simple to complex. The subject then performed six LCT tracks. 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. Participants were reminded of the importance of both tasks and were asked to balance efforts between both. Participants then completed both WM capacity tasks starting with the visuospatial span and following with the letter span.

## DATA COLLECTION

### Lane Change Task (LCT)

Dependent measures, known to be influenced by WM load, were derived from existing literature *(29,34)*.

- Mean deviation in lane change path (MDEV): deviation between the position of the normative model and the actual driven course (Fig. 3). This measure covers several aspect of LCT performance which can result in 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. The normative model was based on baseline level of the participant.
- 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 was used to assess late detection of command signs.
- Percentage of correct lane changes (PCL): the number of correct lane changes that occurred until 40m after the sign. This measure was used to identify cases where signs are missed or incorrectly responded to.

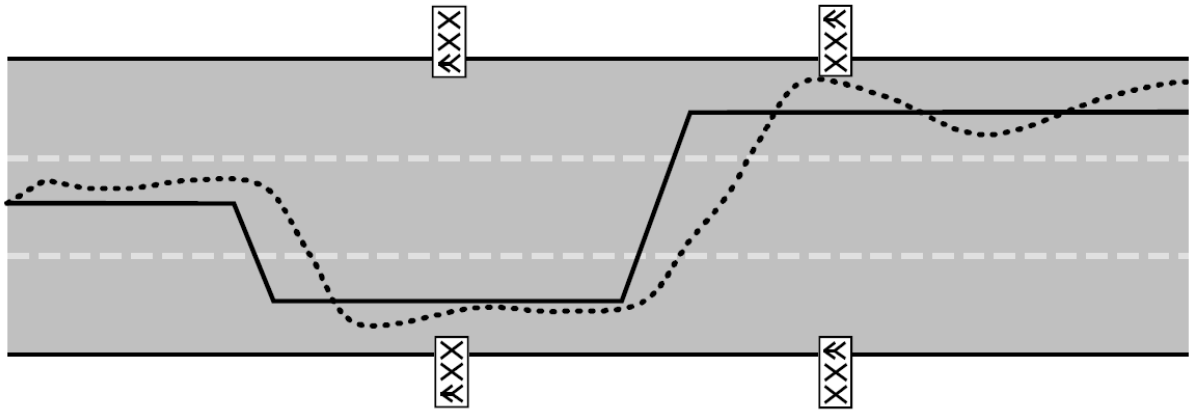

**FIGURE 3 Comparison of normative model and driving data**

### Auditory-Verbal Response N-back

Performance on the verbal WM load task was calculated as the error rate per LCT track and was used as a check for the increasing complexity of the load levels.

## Working Memory Capacity Tasks

*Visuospatial & Letter Span*

For the VS and LS, 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 *(42)*.

## DATA ANALYSES

Exploratory analyses were conducted to identify outliers per verbal WM load level, and per dependent measure, in order to be removed from relevant analyses. Repeated measures ANOVA on the secondary task was conducted to test if the distraction was effective (i.e., more N-back errors with increasing complexity). Repeated measures ANCOVA were conducted to asses: 1) if verbal 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 WM capacity); 3) if the effect of verbal WM load on driving behavior was dependent on WM capacity (interaction effect verbal WM load * WM capacity). Separate models were analyzed per dependent measure.

## RESULTS

### Secondary Task Data

As expected, the increasing complexity of verbal WM load was effective, with more errors being made in more difficult levels ($F(2,86)= 147.2$, $p<.0005$; means: 0-back= 0%, 1-back= 11.04%, 2-back= 45.11%).

### Repeated Measures ANCOVA

MDEV degraded with increasing N-back levels since the main effect of verbal WM load on MDEV was significant ($F(2.1,99.3)= 51.3$, $p<.0005$). MDs between levels showed there was no significant difference between baseline and 0-back (mean difference (MD)= -.02, p= .841) performance, the 0- vs. 1-back (MD= -.14) and 1- vs. 2-back (MD= -.13) did show significant differences ($p<.0005$). There was a main effect of visuospatial ($F(1,47)= 4.4$, $p= .041$, $r= -.454$) and verbal WM ($F(1,47)= 5.5$, $p= .024$, $r= -.472$) indicating that participants with higher verbal and visual WM capacity showed less deviation from the normative path. The interaction effect with verbal WM load was not significant for visuospatial, or verbal WM. The MDEV of participants with higher visuospatial and verbal WM was thus not significantly less affected by increasing verbal WM load complexity.

The initial modal of LCI, including visuospatial and verbal WM, did not reveal a significant main effect of visuospatial WM on LCI ($F(1,48)= .1$, $p= .94$, $r= -.201$). A new model, only including verbal WM, was analyzed. Participants initiated lane changes more slowly with increasing N-back complexity level, verbal WM load main effect on LCI was significant ($F(2.29,112.32)= 80.1$, $p<.0005$). MDs were significant across for baseline vs. 0-back (MD= -.9, $p<.0005$) and 0- vs. 1-back (MD= -1.52, $p<.0005$), and 1- vs. 2-back levels (MD= -.78, p= .009). Verbal WM main effect was significant ($F(1,49)= 7.2$, $p= .01$, $r= -.358$), participants with higher verbal WM displayed lower LCI values. The interaction effect was not significant and therefore LCI of participants with higher verbal WM was not significantly less affected by increasing verbal WM load complexity.

Participants made more erroneous lane changes with increasing N-back complexity since the verbal WM load main effect on PCL was significant (F(1.7,64.58)= 22.5, p<.0005). MDs showed no significant difference between baseline and 0-back (MD= .41%, p= .646) performance. The 0- vs. 1-back (MD= 1.9%, p= .009) and 1- vs. 2-back (MD= 2.58%, p= .010) differed significantly. Visuospatial WM had a significant main effect (F(1,38)= 5.3, p= .027, r= .464), participants with higher visuospatial WM overall made less erroneous lane changes. The interaction effect was not significant; participants with high visuospatial WM were not significantly less affected by increasing verbal WM load. Verbal WM did not show a significant main effect (F(1,38)= 1.5, p= .235). The interaction between verbal WM load and verbal WM however was significant (F(1.7,64.58)= 4.7, p= 0.017). This suggests that, for PCL, participants with higher verbal WM were differently influenced by increasing verbal WM load in comparison to those with lower verbal WM. Using a median-split, separate analyses were performed for participants with a low and high verbal WM. The verbal WM load main effect was significant for both the low and high verbal WM group (p= .000). Nonetheless, F-values and MD's were larger for the low verbal WM group indicating more influence due to increasing verbal WM load complexity (low: F(3,51)=11.504, MD's between .926 and 7.409; high: F(3,66)= 10.301, MD's between 0 and 2.9).

In sum, MDEV degraded between 0-, 1- and 2-back load levels. Participants with higher WM capacity showed less overall deviation from the normative path. Nonetheless, participants with high WM capacity were not significantly less influenced by increasing verbal WM load. LCI degraded between baseline, 0-, 1-and 2-back load. Participants with higher verbal WM had smaller overall LCI values. Again, high WM capacity participants were not significantly less influenced by increasing verbal WM load. PCL degraded between 0-, 1- and 2-back load. Visuospatial WM was related to PCL performance. Participants with high visuospatial WM, however, were not less influenced by increasing verbal WM load. However, separate analyses for low and high verbal WM participants showed that even though both groups experienced a negative impact of increasing verbal WM load, PCL of participants in the higher verbal WM group was less affected (Fig. 4).

**FIGURE 4 Interaction between verbal WM and PCL**

## DISCUSSION

The goal of this research was to investigate, for young novice drivers, the influence of WM capacity on LCT performance when combined with verbal WM load. While previous studies already established degrading effects of WM load on driving performance *(27,28,33,30)*, they did not include an interaction with WM capacity. Therefore, this study sought to determine not only if high WM capacity related to better LCT performance in comparison with low WM capacity. It also determined whether young novice drivers with high WM capacity were less influenced by increasing verbal WM

load, so that their performance did not degrade in the same extent as for those with low WM capacity. Due to the verbal nature of the WM load it could be expected that verbal WM would become important to deal with the increasing load, therefore this interaction was especially expected to occur for verbal WM.

The increasing complexity of the verbal WM load was shown to be effective since participants made more errors in the higher N-back levels. This study adds to existing literature describing WM load effects on driving performance *(9,27,22)*. Even though the secondary task did not require visuospatial WM, verbal WM was increasingly loaded and LCT performance degraded for the selected dependent measures (i.e., MDEV, LCI and PCL) *(29,34)*. This replicates previous findings that distraction, as induced by WM load, affects the normative model *(33)*, as well as detection and response selection *(29)*. As distracting tasks, such as cell phone conversations or interacting with auditory in-vehicle devices, like the current verbal WM load imply both storage and manipulation of information *(39)*, these tasks will likely cause similar effects on driving performance. This indeed has been found where younger and older drivers doubled their engagement in rear-end collisions when using hands-free cell phones during simulated driving *(43)*.

WM capacity had a significant influence on LCT driving performance. This replicates and extends previous research which related WM capacity to LCT performance (i.e., measured by MDEV and lateral position) while counting backwards *(40)*. This study, however, was the first to find that participants with high WM capacity also display a better performance on measures of detection (LCI) and response selection (PCL). More specifically, participants with higher visuospatial WM performed better on MDEV and PCL while participants with higher verbal WM performed better on MDEV and LCI. The multiple recourses theory states that separate dimensions of resources exists, one being the "codes of processing dimension" and this indicates that visuospatial activity uses different resources than verbal activity *(44)*. The found independent influence of visuospatial and verbal WM (PCL vs. LCI) on driving performance provides support for this theory.

Most important, this study was also the first to find that young novice drivers with higher verbal WM were less influenced by increasing load complexity, as reflected by a smaller decrease of correct lane changes in people with high (versus low) verbal WM when load increased. Due to increasing verbal load, verbal WM could alleviate detrimental effects on driving performance which again provides support for multiple resources theories by showing that verbal activity uses different resources then visuospatial activity *(44)*. This result also coincides with theories and findings that the availability of more WM capacity leaves room for greater abilities to use attention for avoiding distraction *(9,45)*. Even though WM capacity was depleted by the verbal WM load, participants with high verbal WM possessed spare capacities which allowed for less interference of the verbal task-irrelevant information while executing the LCT.

## 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 *(29,33)*. 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 selection, such as reacting to slowing vehicles, would show the same interaction with verbal WM when loaded with auditory-verbal WM

capacity tasks. A possible question could be if people with a high verbal WM collide less with slow vehicles in a driving simulation?

## RECOMMENDATIONS

The found relationship between WM and driving performance allows for some possible practical inferences. First of all, training WM capacity might lead to overall better driving performance. More important, it might even, at least for some driving parameters, lead to superior coping with distraction. Training of cognitive control functions, such as WM, to transfer to daily life activities has become popular in the last years. For instance, training WM with a visuospatial N-back task improved simulated driving performance in older adults *(46)*. The additional WM capacity resources that are developed during training could aid in focusing attention at the primary task of driving by diverting it from distracting activities. Training therefore could compensate some of the before mentioned causes that make young novice drivers susceptible to distraction (i.e., low driving experience and less developed WM capacity).

Results from this study allow the consideration of some practical applications. One possible application could be to use WM capacity measures (e.g., VS and LS) to screen young novice drivers for the necessity of training. WM training could then be included in driver learning programs. For instance, a graduated driver licensing (GDL) system already withholds several restrictions for adolescents who are learning how to drive (e.g., limiting nighttime driving and transport of passengers) *(47)*. A possible addition could be a mandatory screening in order to assess whether WM capacity training is necessary. Another option is including such training for every adolescent who wants to obtain his/her license. More research however will be necessary to determine which type of WM training could aid in alleviating detrimental effects of distraction on driving.

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 hand-free technology *(17)*. From this point of view, encouragement of new technologies as the MyKey® system from Ford, which for instance allows parents to limit audio volume, are necessary in order to minimize crash risks due to distraction among young novice drivers.

## ACKNOWLEDGEMENTS

The authors would like to thank Stefan Mattes and Denis Boucher for their assistance concerning LCT analyses. They would also like to thank Bruce Mehler, Bryan Reimer & Jeffery A. Dusek for providing materials for the auditory-verbal N-back. Lastly, they would also like to thank Katrijn Houben and Michiel Vestjens for providing the working memory tasks.

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