SCENARIO CRITICALITY DETERMINES THE EFFECT OF WORKING MEMORY LOAD ON BRAKE RESPONSE TIME

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ABSTRACT: Several experimental studies have found delayed braking reactions due to non-visual working memory loading tasks such as phone conversation. However, these results seem to be at odds with recent naturalistic driving studies which have failed to find any increased crash or near-crash risk due to working memory load. A possible reason behind this discrepancy, in the case of rear-end crashes, is that the effect of working memory load on brake depends on scenario criticality. This possibility was investigated by means of a meta-analysis on a set of existing experimental studies. The results suggested a strong linear relationship between the magnitude of the response delay due to working memory load and the initial time headway at lead vehicle brake onset. A potential mechanism behind this effect is suggested and implications for the generalisation of experimental brake response time data to real world lead vehicle braking scenarios are discussed.

1 INTRODUCTION

Recent naturalistic driving studies have provided strong evidence that driver distraction leads to increased crash risk [1-3]. For example, for a truck driver that is texting on the cell phone, the relative crash risk has been estimated to increase by 23 times compared to normal driving [3]. However, these studies have only found increased crash risk for activities that require visual interaction. Non-visual tasks, such as cell-phone conversation, where not associated with any elevated crash risk. Olson et al. [3] even found reduced crash risk while conversing on the phone. In line with these results, Young and Schreiner [4], who recently analysed airbag deployment crashes automatically reported to the OnStar call centre, found no increased crash risk associated with hands-free phone conversation.

However, these results remain controversial as a large body of experimental simulator and field studies have found delayed braking responses to critical events - typically a lead vehicle braking - during concurrent performance of working memory loading (often referred to as "cognitively loading"), but non-visual, tasks such as, for example, phone conversation and speech interface interaction [5-10]. Since timely responses to potential obstacles is critical for safe driving, it seems reasonable to assume that also working memory loading tasks would have significantly negative effects on road safety. Still, this conclusion is strongly at odds with the results from naturalistic field studies.

What could be the reason for this discrepancy? One reason may be difficulties to detect all forms of working memory load in the video-based analyses typically employed in naturalistic driving studies. However, the fact that phone conversation, which should be easily detected from video, has not been found to increase crash or near crash risk makes it more likely that the discrepancy is due to some confounding factor in the experimental studies. A closer examination of the variability of the response delays associated with working memory load reported in existing experimental studies indeed reveals that the magnitude of the measured response delay varies substantially. For example, Salvucci and Beltowska [10] found a response delay due to working memory load of about 50 ms (for their most demanding task) while Alm and Nilsson [5] found delays of up to 1500 milliseconds! A closer qualitative look at the methodologies employed in the different studies indicate that the measured braking response delay due to working memory load may be related to the criticality of the braking scenarios employed, in particular the headway at the moment of lead vehicle braking, henceforth referred to as the initial time headway. For example Alm and Nilsson, 1995, who found the largest effects of the studies cited above, controlled the initial distance headway to 75 m (implying a time headway of 3 s, assuming equal initial vehicle speeds of 90 kph) while, for example, Salvucci and Beltowska [10] used a 20 m headway at speeds ranging from about 50-120 kph (implying time headways of 0.6-1.4 s) and, as just mentioned, found much smaller effects. If working memory load mainly causes large response delays in non-critical scenarios (with long initial headways), this may give a hint why purely non-visual tasks have not been found to increase crash risk in naturalistic driving studies. The objective of the present study was to further investigate this hypothesis quantitatively by means of a meta-analysis of a set of existing experimental studies, looking specifically at the relation between the initial time headway and the response delay attributed to working memory load.

2 METHOD

Six studies were selected for the present meta-analysis. The common denominator of these studies was that they investigated the effect of working memory load on braking responses in a lead vehicle braking scenario. Moreover, all studies used repeated braking events with some temporal randomization to reduce expectancy. However, the studies also differed in several important ways. Five of the six studies were conducted in driving simulators while one [6] was conducted in real traffic (where an experimenter-controlled lead vehicle generated the experimental braking events). Two of the studies [5, 7] compared groups of older and younger drivers. Two studies varied the complexity of the driving environment, where Lee et al., [9] defined complexity in terms of traffic density, intersection density and scenery (houses, barns, fences, and animals) while Strayer et al. [8] only varied traffic density. One study [10] varied the demand of the working memory task. Five studies used brake response time as the main dependent variable while one study [9] used accelerator release time. Finally, the studies investigated different working memory loading tasks, including real phone conversations [7, 8], different "artificial" working memory tasks [5, 6, 10] and speech interface interaction [9]. An overview of the studies included in the analysis is given in Table 1.

Based on the information available in the respective papers, initial time headway was estimated for each study and condition, leading to a total of 11 data points. The basis for these calculations is provided in table 2. Since the reporting of kinematic conditions is somewhat incomplete in several papers, some assumptions and approximations were necessary. For example, some studies controlled the initial distance or time headway experimentally (e.g. by coupling the lead vehicle's speed to the subject vehicle's speed [5, 9]) while others let the drivers chose their own speed and/or headway. In the latter case, the reported average speed/headway values were used for the initial time headway calculation. In other cases, the actual speed and headway values are not reported, but a reasonable estimation could be made based on the reported instructions to the subjects (e.g. [6]). In a few cases, speed information was missing altogether (e.g. in [8], and for the baseline condition in [5]). Here, values were assumed based on the road type used and/or the speed reported for the experimental conditions. Values which were not reported in the text had to be approximated from the graphs. When not provided directly (as in [9]), the initial time headway was estimated from the initial distance headway divided by the initial speed (assuming equal speeds of the lead and subject vehicles). For [10], the average initial time headway for the four randomly varied initial speeds was used.

Table 1 Overview of the studies included in the present analysis (BRT=Brake response time; ART=accelerator release time)

Study	Type of study	Scenario	Working memory task	Response metric	*Additional conditions*
Alm and Nilsson [5]	Simulator	Lead vehicle braking intermittently during car following at rate 4 m/s2. Initial distance headway controlled at 75 m. Speed self paced.	Working Memory Span Test	BRT	*Young/Old drivers*
Brookhuis et al. [6]	Field	Lead vehicle braking intermittently during car following (deceleration rate not reported). Speed instructed to 95 kph and distance headway to 40 m (averages not reported).	Forced pace memory test via mobile phone	BRT	-
Lee et al. [9]	Simulator	Lead vehicle braking intermittently during car following at rate 2.1 m/s2. Initial time headway controlled at 1.8 s.	Speech control of email system	ART	*Simple/complex driving environment*
Salvucci and Beltowska [10]	Simulator	Lead car braking at 3, 6, 9 or 12 s during a 20 second driving epoch (the braking initiation point was randomised between trials). Speed and headway was	Silent rehearsal of lists of digits	BRT	*5 or 9 items for rehearsal*

Study	Type of study	Scenario	Working memory task	Response metric	*Additional conditions*
		controlled. Speed increased from zero to 120 during the 20s interval. Initial distance headway was always 20 m.			
Strayer and Drews [7]	Simulator	Lead vehicle braking intermittently during car following. Deceleration rate not reported. Speed and headway self-paced.	Phone conversation on topics chosen from a list by the subject	BRT	*Young/Old drivers*
Strayer et al. [8]	*Simulator*	*Lead vehicle braking intermittently during car following. Deceleration rate not reported. Speed and headway self-paced.*	*Phone conversation on topics chosen from a list by the subject*	*BRT*	*Low/high traffic density*

3 RESULTS

Response times (RT) for the baseline and working memory conditions against initial time headway (THW) are plotted in Figure 1. Linear regression analyses yielded the following relationships for the baseline (BL) and working memory (WM) conditions respectively1. The regression lines are also plotted in Figure 1.

RTBL=445×THW+286 (F(1, 8)=60,8, r2=.88, p<.01) (1)

RTWM=882×THW-112 (F(1, 8)=64.3, r2=.89, p<.01) (2)

[1] In the analysis of absolute RT, the study by Brookuis et al. [6] was excluded here since only the difference between conditions, not absolute RTs, are reported in the paper.

Table 2 Estimation of initial time headway. BL=baseline, WM=working memory load; THW=initial time headway, DHW=initial distance headway; NR=not reported; contr.=controlled experimentally to a fixed value; av.=average value in self-paced conditions; instr.=derived from experimental instructions; ass.=assumed; graph=value approximated from graph

Study/ condition	Baseline RT (ms)	WM RT (ms)	Resp delay (ms)	BL init. speed (kph)	WM init. speed (kph)	BL DHW (m)	WM DHW (m)	BL est. THW (s)	WM est. THW (s)	Est. Av. THW (s)
Alm and Nilsson [5], young	1620 (graph)	2190	560	NR; 87.5 ass.	87.5 (av.)	75 (contr.)	75 (contr.)	3.09	3.09	3.09
Alm and Nilsson [5], old	1930 (graph)	3480	1460	NR; 77.4 ass.	77.4 (av.)	75 (contr.)	75 (contr.)	3.49	3.49	3.49
Brookhuis et al. [6]	NR	NR	130	95 (instr.)	95 (instr.)	40 (instr.)	40 (instr.)	1.52	1.52	1.52
Lee et al. [9], simple driving	820	1200	380	64.4-72.4 (instr.)	64.4-72.4 (instr.)	NR	NR	1.80 (contr.)	1.80 (contr.)	1.80
Lee et al. [9], complex driving	1200	1400	200	64.4-72.4 (instr.)	64.4-72.4 (instr.)	NR	NR	1.80 (contr.)	1.80 (contr.)	1.80
Salvucci and Beltowska [10] 5 digit list	555 (graph)	555 (graph)	0	87,3 (contr., av.)	87,3 (contr., av.)	20 (contr.)	20 (contr.)	0.89	0.89	0.89
Salvucci and Beltowska [10] 9 digit list	555 (graph)	600 (graph)	45	87,3 (contr., av.)	87,3 (contr., av.)	20 (contr.)	20 (contr.)	0.89	0.89	0.89
Strayer and Drews [7], young	780	912	132	102.0 (av.)	100.1 (av.)	22.7 (av.)	26.4 (av.)	0.80	1.06	0.92
Strayer and Drews [7], old	912	1086	174	84.5 (av.)	86.6 (av.)	37.1 (av.)	40.7 (av.)	1.58	1.63	1.60

Study/ condition	Baseline RT (ms)	WM RT (ms)	Resp delay (ms)	BL init. speed (kph)	WM init. speed (kph)	BL DHW (m)	WM DHW (m)	BL est. THW (s)	WM est. THW (s)	Est. Av. THW (s)
Strayer et al. [9], low density	928	957	29	NR; 90 (assumed)	NR; 90 (ass.)	25.8 (av.)	29.3 (av.)	1.03	1.17	1.10
Strayer et al. [9], high density	933	1112	179	NR; 90 (assumed)	NR; 90 (ass.)	23.6 (av.)	26.0 (av.)	0.94	1.04	0.99

As is clear from Figure 1 and the regression equations above, initial time headway was strongly predictive of response times, accounting for an estimated 88-89% of the RT variability. For the baseline condition, the derived model predicts that a 1 second increase in THW will lead to a 445 ms increase in RT. The corresponding predicted increase for the working memory condition is 882 ms. The steeper slope in the working memory condition indicates that not only absolute RT values, but also the magnitude of the response delay caused by working memory load (i.e. the difference between the average response times in the baseline and experimental conditions) depends on initial time headway.

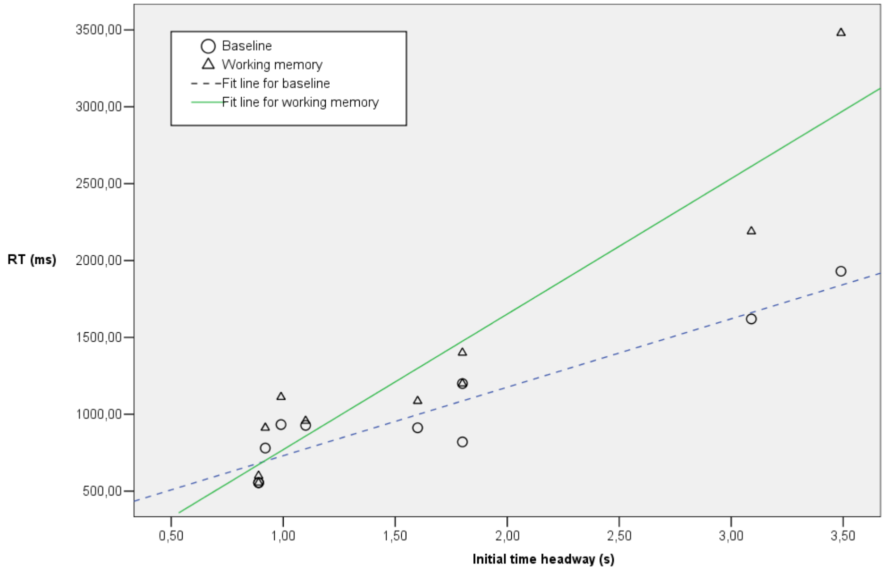

Figure 1 Response time as a function of initial time headway for the baseline and working memory conditions, with regression lines.

In a further regression analysis, the reported response delay due to working memory load was related to initial THW. When the estimated initial THW values for baseline and working memory conditions differed (e.g. due to different reported speeds), the average value was used in the calculation (i.e. the value in the rightmost column in Table 2.

This resulted in the following model:

Response delay= 416×THW-385 (F(1,9)=33.5, r2=.79, p<.01) (3)

Hence, initial THW accounted for 79% of the variance in the reported response delay attributed to working memory load and the model predicts that the delay increases by 416 ms for every 1 second increment in initial THW. The data and the fitted regression model are plotted in.

4 DISCUSSION

The present analysis demonstrated that:

Response time increases with initial time headway, both in baseline and working memory conditions (Equation 1 & 2, Figure 1)

RT depends more strongly on initial time headway in the working memory condition (Equation 1 & 2, Figure 1)

As a consequence of (2), the response delay due to working memory load (i.e. the difference between RT in the working memory and baseline conditions) also increases with initial THW (Equation 3,). Thus, the longer the initial time headway, the larger is the effect of working memory load on response time.

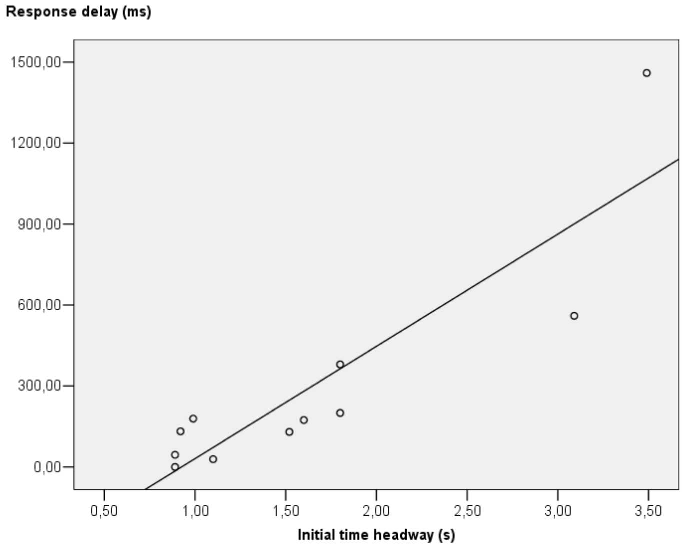

Figure 2 Reported response delay due to working memory load plotted against estimated initial time headway for the studies and conditions listed in table 2.

The strength of the relationships in Equations 1-3 is particularly striking given the substantial differences between the studies and conditions with respect to experimental settings, working memory tasks, subject age and driver environment complexity. However, it should be noted that, due to the uncertainty involved in estimating initial time headways for some of the studies and the few data points available for longer headways (implying a heavy reliance of the obtained regression model on Alm and Nilsson's [5] data), the present results should be viewed as preliminary and treated with caution.

So why does working memory load delay braking responses and why should this effect depend on initial time headway? A theoretical model addressing the first question is offered by Salvucci and Beltowska [10], who propose that the delay occurs since the braking and working memory tasks compete for a "central executive" which processes information in a serial fashion. Hence, when the central executive is loaded by working memory operation, braking cannot be initiated until the rehearsal of the last item in working memory is completed. However, in their study, only the more demanding working memory task (rehearsal of a list with 9 items) delayed braking responses, while the lower-demand task (rehearsal of 5 items) did not, which contradicted the prediction of their model. In an attempt to account for this discrepancy, the authors proposed a revised model which also takes into account the urgency of the different tasks; in this case, rehearsing the 9-item list could be regarded as more urgent than the 5-item list and thus have a stronger effect in delaying the braking response. While this revised model may perhaps also be invoked to explain the present finding that the magnitude of the response delay depends on scenario criticality (on the assumption that braking responses in non-critical scenarios are less urgent and thus down-prioritised in favour of the working memory task), it does not provide any clear account of the mechanisms behind this dual task trade-off in lead-vehicle braking scenarios.

An alternative explanation can be outlined as follows: It may be assumed that braking responses in lead vehicle braking situations are triggered by two main types of visual stimuli: (1) the onset of the lead vehicle's brake lights and (2) the perceived optical expansion of the closing lead vehicle, which is commonly referred to as looming (e.g. [11]).2. The threshold at which a looming lead vehicle begins to be experienced as a hazard by the following driver could be considered as a subjective comfort zone boundary that the driver attempts to avoid exceeding [13, 14]. The looming cues that perceptually define the comfort zone boundary can be assumed to trigger braking responses "automatically" in a stimulus-driven, or bottom-up, way. Brake light onsets may also attract visual attention bottom-up. However, by contrast to looming, brake light onsets do not automatically trigger braking responses (since an immediate response is normally not motivated as long as the situation is not critical). Rather, in normal driving situations the brake light onset functions as an alert signalling that a braking response may be required. Thus, brake lights trigger braking responses via top-down, expectancy-driven, attention and action selection mechanisms. An extreme case of top-down driven responses occurs if the driver (1) expects

[2] As first demonstrated by Lee [12], looming specifies time-to-collision in terms of the *tau* (τ) parameter, which equals the angular size of the closing object divided by its derivative (i.e. the angular change rate). However, whether *tau* is the only optical parameter that drivers use to decide when to initiate braking is still debated. For present purposes, it suffices to say that looming cues (tau and/or others) determine the perceived criticality of the situation and may trigger emergency avoidance reactions.

that the lead vehicle will brake and (2) is motivated to respond as quickly as possible. This type of situation is probably rare in real world driving but common in laboratory experiments. In this case, the subject can exploit top-down attention selection to respond quickly to brake lights, even if the headway to the lead vehicle is large and the driver feels well within his/her comfort zone. Evidence from laboratory studies suggests that working memory load interferes more with top-down than bottom-up selection [e.g. 15]. It could thus be hypothesised that working memory load will interfere with (top-down) responses to brake lights but leave (bottom-up) responses triggered by looming cues relatively unaffected.

In all studies included in the present meta-analysis, the braking events were repeated and the subjects thus expected that the lead vehicle would brake, although they did not know exactly when. Moreover, in several of the studies, studies subjects were informed about the braking events prior to the trials and sometimes even instructed to respond as quickly as possible to the braking lead vehicle [5, 10] (detailed information on prior instructions are generally lacking in the other papers). Thus, a compliant subject would both expect the braking events and be motivated to respond as fast as possible, regardless of scenario criticality. Hence, in baseline conditions, braking responses would be relatively fast. Some dependency on initial headway could be expected, however, given that the saliency of the brake light depends on headway (especially on simulator screens with limited resolution). By contrast, in working memory loading conditions, top-down driven responses to the brake lights are impaired. Thus, the triggering of braking responses has to rely on bottom-up looming cues at the comfort zone boundary. In this case, the response time depends on when the comfort zone boundary is reached which, in turn, depends on the initial time headway. This offers an explanation for the stronger dependency of response time on initial time headway in the working memory load conditions, which leads to an increased effect of working memory load when initial time headway increases. The proposed mechanism is further illustrated in Figure 3.

One implication of this model is that the effect of working memory load on response time in experimental studies would be strongly reduced if the brake lights are turned off. This hypothesis has not, to our knowledge been directly tested experimentally. However, some support can be found in a study by Muttart et al. [16] which investigated responses to a slowing lead vehicle in simulated road construction areas with the brake lights turned off. The authors did not find any effect of working memory load in "standard" lead vehicle slowing scenarios (however, an effect was found when the lead vehicle slowing was predicted by an event further down the road).

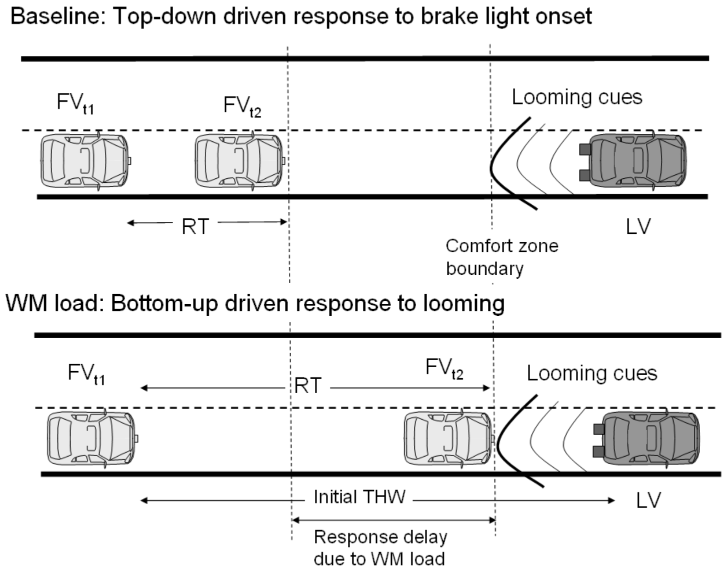

Figure 3 Illustration of the hypothesised mechanism behind the relation between initial time headway and response delays due to working memory load. FV=following vehicle; LV=lead vehicle; t1=time at LV brake onset; t2=time at FV brake onset. See the text for further explanation.

According to the suggested model, looming cues serve as a “back-up” that trigger last-second braking responses bottom-up when top-down expectations fail or when, as in the present case, the top-down selection is impaired by working memory load. Thanks to this protective mechanism, rear-end crashes in the real world may be avoided even when responses are delayed, as long as the hazard occurs within the field of view. It follows that that the key critical condition that would be expected to contribute to rear-end crashes is when eyes are directed off the forward roadway so that both brake lights and looming cues are missed. Indeed, recent naturalistic driving studies provide strong evidence that eyes off road is the key factor behind rear-end collisions [1-3]. Thus, the present results hints at a possible explanation for the apparent discrepancy between naturalistic and experimental studies with respect to the effect of working memory load on crash risk, at least in rear-end crash scenarios. However, controlled experiments are needed to test these ideas more rigorously.

It should also be noted that this does not rule out that working memory load may contribute to crashes in more subtle ways. For example, the impaired ability to use predictive symbolic or environmental cues under working memory load demonstrated, for example, by Muttart et al. [16] and Baumann et al. [17] may be an important factor behind the evolution of critical situations. In particular, an impaired understanding, due to working memory load, of how a traffic scenario will evolve could be a key reason why a driver decides to take the eyes off road at the wrong moment. This hypothesis could be further investigated in both experimental and naturalistic driving studies. In the latter case, the video-based analysis could possibly be complemented by driver interviews in order to capture all forms of working memory load and its potential impact on drivers' situation understanding.

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