Laboratory Rotation
-Report

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Time course of visual short-term representation in a dynamic collision-avoidance task

Contents

Abstract

The experiment conducted in the course of this laboratory rotation aimed at measuring the persistence of memory representations in a virtual collision-avoidance task. Subjects were instructed to cross an intersection in a car without colliding with the cross-traffic. In some of the trials the cross-traffic was occluded while the subjects were approaching the intersection. After a delay the occluder disappeared and the subjects were asked to reconstruct the scene last observed out of memory. I assessed the influence of delay duration and found that it neither affects the amount of remembered items nor the recall time per item. However, it influences the accuracy of scene reconstruction. In trials containing long delays positioning was less accurate than in trials containing short delays. Furthermore, cars relevant for collision-avoidance were more likely to be remembered than cars irrelevant for collision-avoidance.

1 Introduction

1.1 Working memory

The paradigm used in this experiment was designed to investigate working memory in a dynamical environment. The term working memory refers to the theoretical concept of a low capacity storage system acting between perception, long-term memory and action (Baddeley, 2003). The most prominent model of working memory in current research was developed by Baddeley and Hitch in 1974 (Baddeley and Hitch, 1974). They proposed a multicomponent system that facilitates the mastering of complex cognitive tasks such as learning, reasoning and comprehension. The model holds that an attentional system of limited capacity, called the central executive, coordinates two subsidiary storage systems: the phonological loop and the visuospatial sketchpad. The idea of separate components is supported by an immense amount of experimental data which show that phonological and visual/spatial short-term memory can be manipulated independently (e.g. Logie et al. 1990; Shah and Miyake 1996). More recently the so-called episodic buffer was added as a fourth component in order to account for a number of observations not explained by the original model, such as binding of memories of different modalities (Repovs and Baddeley, 2006). The terms working memory and short-term memory are often used synonymously in modern literature.

1.2 Capacity limits of working memory

Limited capacity is a key feature of working memory. In particular, visual short-term memory (alias visuospatial sketchpad) can only store a few aspects of the environment at a time. This characteristic results in a phenomenon known as change blindness: The ability to report objects that have moved, disappeared or changed colour from one presentation of a scene to the next depends heavily on the number of changes to be detected and is in general very limited (Simons and Levin, 1997). Luck and Vogel established that observers are able to retain up to four features of the same dimension, e.g. colour, and can do so for three to four dimensions (Vogel et al., 2001; Luck and Vogel, 1997). This way subjects may remember up to four objects with four features each. Luck and Vogel concluded that information is stored in form of objects and that working memory can store roughly four objects at a time. Their results support the idea of a “magical number four“ in visual attention (Cowan, 2001) and gave rise to a yet ongoing debate about the form in which information is stored. The hypotheses of Luck and Vogel have been questioned by a number of authors (Davis and Holmes, 2005; Olson and Jiang, 2002; Wheeler and Treisman, 2002; Saiki, 2003).

In summary, researchers agree that capacity of working memory is limited. Furthermore, it has been suggested that there is a fixed capacity limit between three and five items in a number of unrelated studies (Cowan, 2001). However, the idea of a fixed capacity is still under debate, with objecting views ranging from rejection to rather light modifications (see open peer commentary to Cowan, 2001). Part of the criticism is based on that fact that some studies suggest a capacity limit other than four (e.g. Miller 1956; Yu et al. 1985). Proponents of a "magical number four" suggest the phenomenon of chunking as a possible explanation for divergent estimations of the supposed capacity limit (Cowan, 2001). Indeed, the ability of subjects to associate bits of information and to store them as chunks poses a problem to the estimation of capacity limits and could lead to overestimation.

1.3 Capacity limits of working memory in dynamic environments

Compared to the numerous studies on capacity limits in stationary set-ups, little is known about the effects of motion on working memory. Data indicating the existence of a four-object-limit in dynamic environments, as it was proposed for static situations, were presented by Pylyshyn and Yantis (Pylyshyn and Storm, 1988; Yantis, 1992). More recent studies cast doubt on the idea of fixed capacity limit. Experiments by Saiki show that performance on visuospatial working memory tasks depends on the speed of the presented items (Saiki, 2003). With increasing speed memory performance declines, even when retention capacity in terms of numbers is far from exhausted. On the other hand, slow velocities allow multiple targets to be attended to.

Alvarez and Franconeri showed that up to eight targets can be successfully tracked at low velocities (Alvarez and Franconeri, 2007). Moreover, Saiki reports that motion heavily impairs feature binding. When dynamic updating of features of moving targets is required, every additional target leads to a markable decrease in performance on change detection, starting with the first additional target. By contrast, performance breaks down approximately with the fourth additional item in static situations (Luck and Vogel, 1997).

These results emphasize the influence of movement on the establishment of memory representations and the need for further research in this direction. Thus a new dynamic working memory paradigm was developed in our laboratory, which could be used to investigate matters such as capacity limitations of visuospatial working memory in dynamic environments. In this study it was employed to address the effects of delayed recall.

1.4 Models of forgetting

Much like the existence of a fixed, object-based capacity limit, the role of time in the forgetting of recently presented material is the subject of a lively debate. Early studies regarding this issue seemed to equivocally support the intuitive notion that memory traces decay over time spontaneously. For example, Brown as well as Peterson and Peterson could show that memory for letters is rapidly lost over time while subjects are engaged in some distractor task in between item presentation and recall, such as counting backwards (Brown, 1958; Peterson and Peterson, 1959). Consequently, temporal decay was adopted as a core principle in many models (e.g. Baddeley 1976; Brown et al. 2000; Page and Norris 1998; Glenberg and Swanson 1986). In particular, the model of Baddeley and Hitch assumes that memory representations stored in working memory decay quickly in case they are not rehearsed through the articulatory rehearsal process embedded in the phonological loop (Baddeley, 2003). However, the role of time in forgetting proved much harder to interpret than it was first thought.

The first challenge to the concept of temporal decay was brought forward by Turvey et al who used a modification of the Brown-Peterson paradigm (Turvey et al., 1970). They had different groups engage in the distractor task for different durations and could not find differences in memory performance between the groups. Interestingly, memory performance changed abruptly when the interval in between presentation and recall was changed from one trail to the next. These findings gave rise to the thesis of temporal distinctiveness, which states that temporally isolated items will be remembered more reliably than items which are part of a sequence with a fixed inter-presentation interval (e.g. Nairne et al. 1997). These items are, so to say, salient in time. Thus forgetting results from the difficulty not to confuse information from the last trial with information stemming from previous trials. In line with these considerations, it is argued that forgetting in the Brown-Peterson paradigm is not due to the passage of time per se but rather to interference with previous input (Keppel and Underwood, 1962).

Supporting the concept of interference, Nairne et al. reported that temporal decay is hardly observed even for long delays when interference between trials is kept minimal by presenting new material on each trail (Nairne, 1999). Inspired by these results, a number of authors presented models of short-term memory which assume that the passage of time has only an indirect role in forgetting in that it provides opportunity for interference to occur (e.g. Henson 1998; Farrell and Lewandowsky 2002; Nairne 1990; Murdock 1995).

Evidently, the rejection of time as a cause for forgetting stands in conflict with Baddeley's model of working memory and other models with similar assumptions. The word-length effect is a key issue in this heated debate. The expression refers to the fact that immediate memory span declines as the words to be remembered increase in length (Baddeley et al., 1974). Proponents of temporal decay argue that long words are harder to remember because they take more time to be articulated and are therefore rehearsed more slowly than short words (Baddeley, 2003; Mueller et al., 2003). Opponents favour word complexity (e.g. Caplan et al. 1992) and/or interference (e.g. Lewandowsky et al. 2004) over rehearsal duration as the cause for the word-length effect. Matters are made more complicated by the observation that rehearsal can take place even under articulatory suppression (Hudjetz and Oberauer, 2007). On the one hand, proponents of temporal decay can always point to rehearsal in case delay duration is found to have no effect on memory performance. On the other hand, opponents can always point to interference in case delay duration is found to have an effect. Resolving the conflict between time-based and interference-based models is one of the most important challenges for future memory research. Importantly for this study, both kinds of models predict that forgetting takes place when interference between trials is not minimized.

1.5 The experiment

To investigate the impairment of driving skills of patients with homonymous visual field defects Hardiess and Mallot developed a virtual reality paradigm which requires subjects to avoid collisions with the cross-traffic at an intersection (Mallot et al., under revision). Subjects are approaching an intersection in a car and are asked to regulate their velocity such that they do not collide with the cross-traffic. The paradigm was extended recently in order to assess memory performance in this condition. In the extended version the cross-traffic is occluded in some of the trials (these trials are henceforth referred to as the positioning-trials) while subjects are approaching the intersection. After a delay they are asked to reconstruct the scene last observed out of memory. To fulfill this task it is necessary to remember the position, the size and the direction of movement of the cars from the intersecting street.

As they were approaching the intersection subjects did not know whether a trail would end with reconstruction or with collision-avoidance. Therefore they needed to prepare mentally for collision-avoidance on every trail (and were instructed to do so), i.e. they had to watch the cross-traffic carefully from the beginning of each trial in order to find a gap to cross the lane. It is assumed that subjects are not able to form detailed long-term representations of their environment under such stressful circumstances but rather store the information relevant for mastering the situation in visuospatial working memory.

The main question to be addressed in this study was whether the duration of delays in between presentation and recall affects the accuracy of scene reconstruction. Additionally, I explored the data produced by the subjects in respect to four further questions:

- Do subjects recall crash-relevant cars to a greater extent than they recall crash-irrelevant cars?
- How many cars are remembered on average?
- Is there evidence for chunking?
- Does the duration of the delay affect the time needed for scene reconstruction?

2 Material

All experiments were performed using a virtual reality environment displayed on a large, curved projection screen. This screen provided a horizontal field of view of 150° and a vertical one of 70° to the subject. The geometrical shape of the projection screen was that of a conic shell with a vertical axis, an upper radius of 1.83 m, and a lower one of 1.29 m. Subjects were seated upright with the back tightly at the chair and with their head in the axis of the conical screen (eye level at 1.2 m with 1.62 m screen distance). Two video projectors (SANYO PLC-XU46 with 1024 x 768 pixel resolution) were used to illuminate the whole screen. The set-up was running on a 2.6-GHz PC under Linux RedHat 9.0 as operating system (graphic card: NVIDIA Quadro4 980XGL with dual video projector connection). The spatial resolution was 2048 x 768 pixels with a frame rate of 60 Hz. Experimental procedures and rendering of the virtual environment was programmed in the SGI OpenGL Performer. Compensation for image distortion generated by the curved screen was programmed in C++. Soft edge blending was done in hardware using two partial occluders in front of the projector lenses. Subjects acted in the virtual environment with the help of a joystick (XTREME 3D PRO, Logitech).

Fifteen subjects participated in this study. Subjects were students at the University of Tübingen with normal or corrected to normal vision and were naive to the purpose of the experiment. They received monetary reimbursement for their participation.

3 Methods

3.1 The virtual environment

The virtual scenario designed for this study consisted of two intersecting streets in an otherwise rather empty environment, both of which emerged from and led into tunnels. Subjects perceived the scene from the perspective of a car driver approaching the intersection. While they were the only road user on their road, the intersecting street was heavily populated. The cross-traffic consisted of cars of three sizes (small, medium and large), with cars heading to the left being red and cars heading to right being white.

3.2 The task

The experiment comprised 60 trials, each of which either required the avoidance of a collision with the cross-traffic or the reconstruction of the scene last observed. Subjects did not know and could not predict which kind of trial would come next. There were 20 traffic situations in total which were presented in pseudo-random order. Out of the 20 situations 7 were used for positioning-trials. The 7 positioning trials were preceded by delays during which subjects had to count loudly. Delays were either 1, 5 or 30s and every situation that was used for positioning occurred once with each delay (so there were 21 positioning-trials in total).

At the beginning of each trial subjects were approaching the intersection with a speed of 30 km/h. After 3.7s the occluder either flashed up shortly in case it was trial which required avoidance of collision or – in case it was a positioning-trial – stayed for the delay associated with the trial.

When collisions were to be avoided subjects gained control over the velocity of their car at that point until they reached a white line very close to the intersection. They could speed up or slow down by pushing the joystick forward or by pulling it backward respectively. However, they could not stop the car. When they reached the white line the car continued with the speed last set by the subject. The traffic situations were designed such that the subject´s car would reach the intersection after 4.2s and collide with one of the crossing cars if the subject did not alter the speed. Following the arrival at the intersecting street the scene faded, i.e. there was no feedback regarding the successful avoidance of a collision.

In a positioning-trial the virtual environment changed after the occluder disappeared. Subjects saw a collection of cars above the crossing street. They could select cars from the full set of cars existing in the virtual world by pressing the fire button of the joystick and position them on the crossing street in the same manner. They had 30s to position the cars they remembered. The remaining time was indicated by a shrinking bar. After positioning time elapsed subjects had another 20s to correct the positions of already positioned cars, with the remaining time being displayed the same way. If subjects finished the positioning or the correction well before the time limit was reached they could ask the experimenter to start the next trial.

4 Results

4.1 The effect of relevance

In the first step of data analysis just the number of positioned cars was considered, irrespective of the accuracy of scene reconstruction. To avoid crashes it is necessary to pay attention to cars approaching the intersection. Cars which have already passed the intersection are irrelevant for collision-avoidance. Therefore it seems reasonable that subjects pay attention rather to approaching cars than to leaving cars and that these cars are present in memory to a greater extent. To test this hypothesis I examined the positions of the cars that were placed by the subjects in the reconstruction condition. In the reconstruction environment subjects could oversee about 130m of street to the left of the intersection and 130m to the right of the intersection. I divided this part of the intersecting street into bins of ten meters. Figure 1 shows the average percentage of cars positioned in each bin over the whole experiment.

Most of the cars positioned by the subjects were facing the intersection (Figure 2), indicating that arriving cars are represented in memory to a greater extent than leaving cars. Furthermore, the majority of cars was positioned close to the intersection. Most cars were positioned not further than 30m away from the intersection. Only on very rare occasions was a car placed more than 60m away from the intersection. The results show very clearly that cars approaching the intersection dominate memory representations in our paradigm. Compared to the situations presented on the screen the reconstructed scenes showed an excess of cars in the bins closest to the intersection, i.e. subjects overestimated the relative traffic density in these locations.

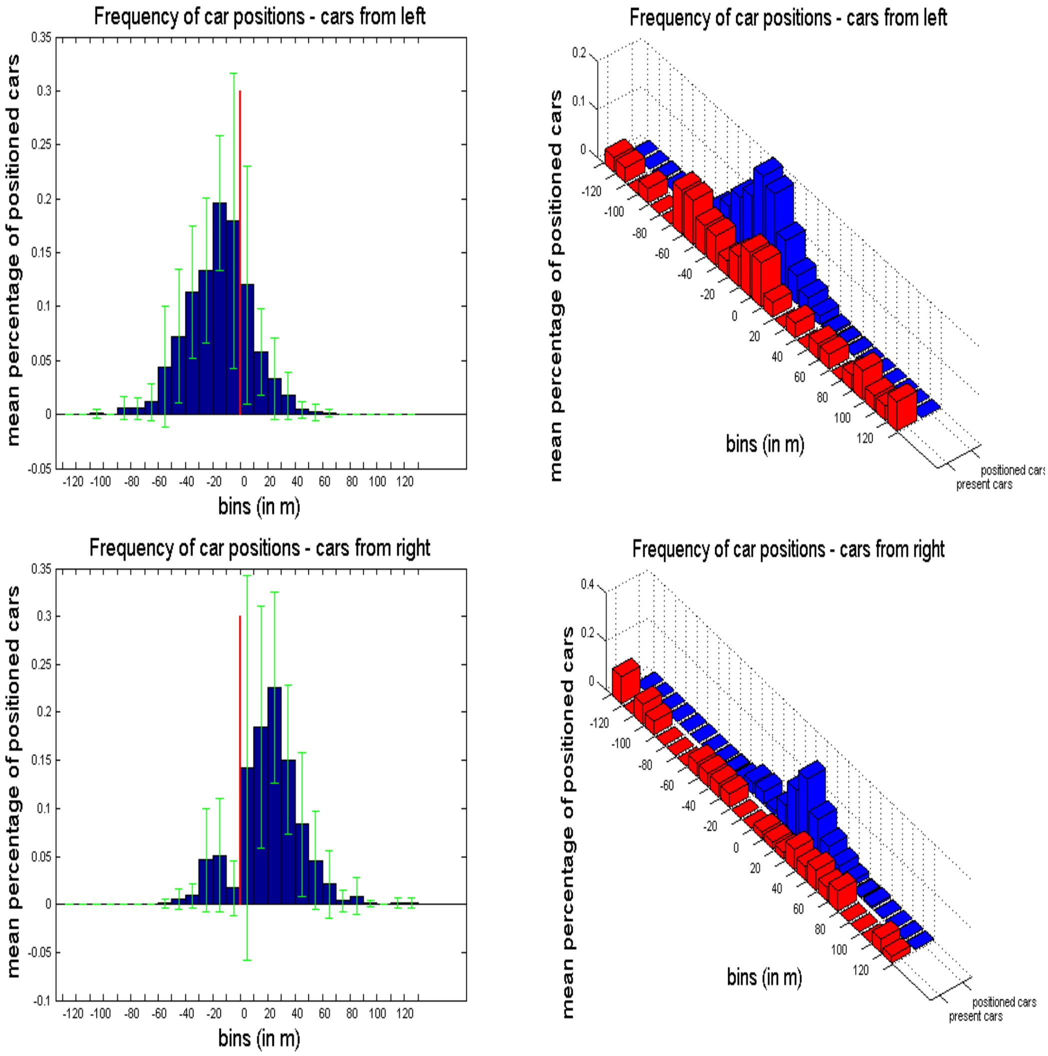

Figure 1: **The figure shows the average number of cars positioned in each bin (left side) and a comparison between the distribution of positioned cars and the distribution of cars which were actually present (right side). The red line in the plots on the left marks the intersection, the green errobars indicate the standard deviations.**

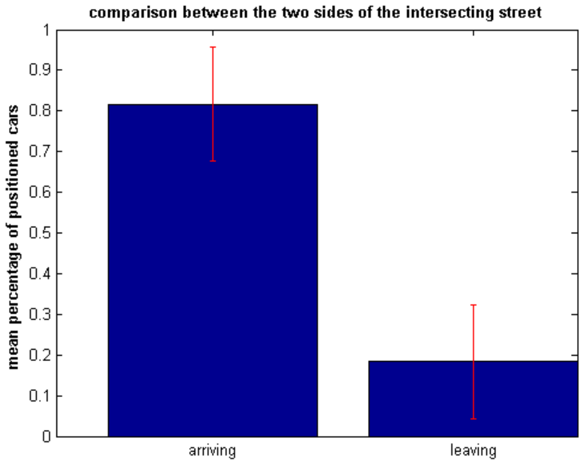

Figure 2: **Mean percentage of cars positioned such that they arrive at or leave the intersection respectively. Red bars indicate the standard deviations.**

4.2 The effect of time on the amount of positioned cars

Forgetting during the distractor task could theoretically manifest in a decrease in the amount of positioned cars and/or in a decrease in positioning accuracy. I found no evidence for forgetting in terms of amounts (compare figure 3). For all three distractor task durations subjects positioned about 29 cars on average in the 7 trials with common delay, i.e. about 4 cars per trial. The average over all trials and subjects was 4.2 cars. The stability of representations in terms of amounts could be observed for every single subject. However, the average amount of cars positioned per trial differed considerably across subjects. For example, one subject positioned only about 1.2 cars per trial while another positioned 6.2 (these were the most extreme cases). The highest amount of cars positioned in one trial was 9.

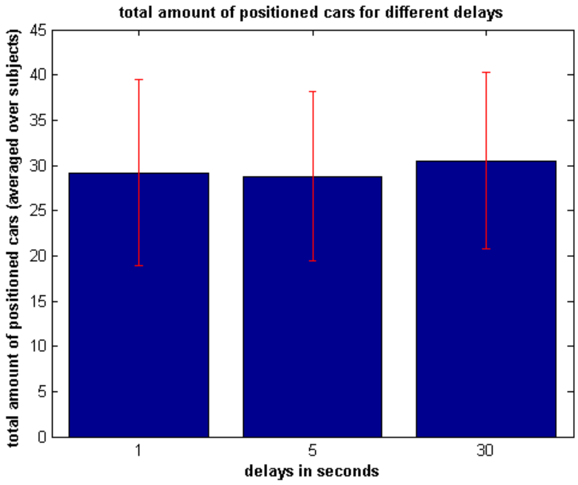

Figure 3: **Total amounts of cars positioned on average in trials with common delay. Red bars indicate the standard deviations.**

4.3 Clustering

When investigating the amount of items which can be remembered in a working memory paradigm it is important to take the phenomenon of chunking into account (Cowan, 2001). To get an idea whether subjects recalled cars en bloc I counted the occurrence of car clusters. I defined a cluster as two or more cars that were positioned such that they form a sequence in space and in time. For example, if one would position a line of three cars, starting with first and ending with the last or vice versa, one would create a triple-cluster. The way cluster is defined here, cars driving into opposite directions cannot form a cluster. In the next step the frequency of clusters was computed for simulated scenes consisting of cars positioned randomly. As shown in figure 4, the scenes created by the subjects contained more clusters than the scenes produced in the simulation, which means that subjects tended to recall neighbouring cars (in the memorized scenes) one after the other. Cluster frequencies were unaffected by the distractor task duration.

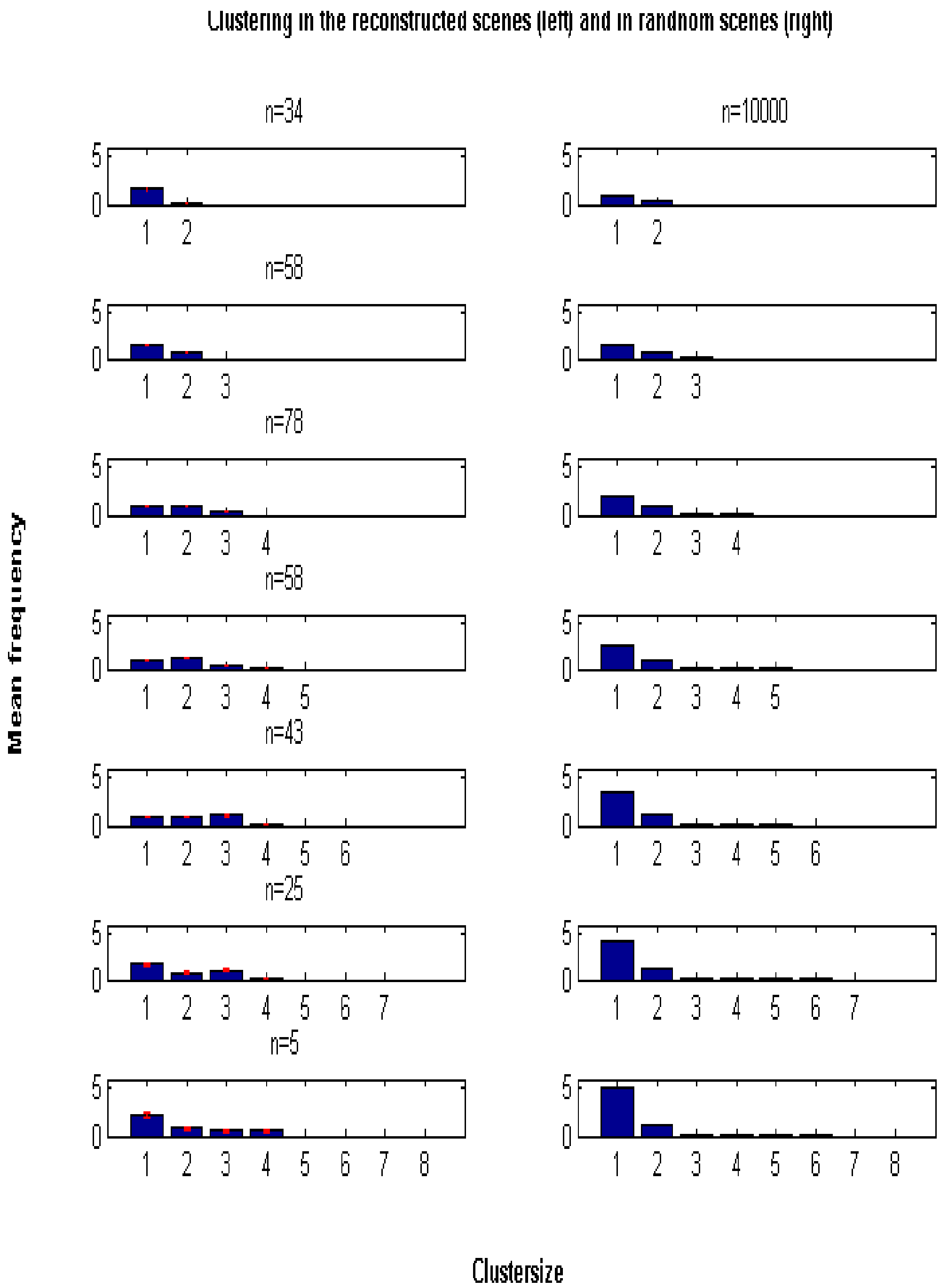

Figure 4: **Average cluster frequencies in the scenes reconstructed by the subjects (left) and in the scenes produced in the simulation (right). In the simulation cars were positioned randomly. Scenes with equal amounts of positioned cars are presented next to each other. The labeling of the horizontal axis indicates how many cars were positioned in total (maximum value in the label). The number number of trials contributing to the averages is shown above the graphs. In all the graphs on the right the average comprises 10 000 scenes. Red bars indicate SEMs.**

4.4 The effect of delay duration on the time needed for reconstruction

It is conceivable that subjects felt less sure of the car positions when a long delay preceded recall and therefore positioned cars slower. Analysis of the time spent on positioning could not verify this hypothesis. The time needed to position a car was independent of the duration of the distractor task. Figure 5 shows the average positioning time plotted versus the distractor task duration. Positioning time was defined as the timespan between the selection of the first positioned car and the positioning of the last car divided by the number of positioned cars.

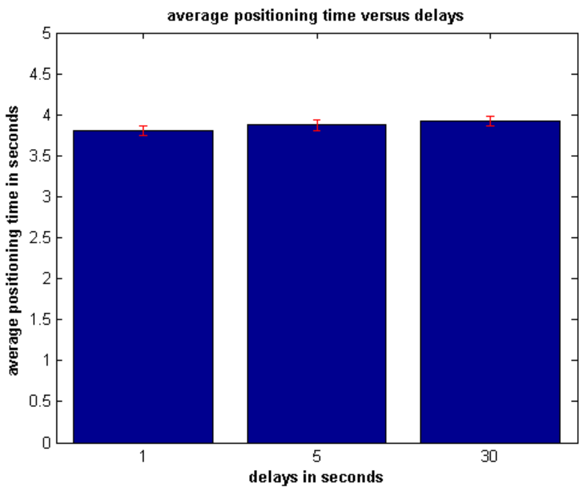

Figure 5: **Mean positioning time plotted versus distractor task duration. Red bars indicate SEMs.**

4.5 The effect of time on positioning accuracy

To determine the positioning accuracy I matched every positioned car to one of the cars which were actually present in the scene last observed by the subject. Matching was done such that the sum of the distances between the positioned and the matched cars was minimal. The positioning error was defined as the minimal sum of distances divided by the amount of positioned cars. The positioning error was calculated for every trial and the trials containing different distractor task durations were compared. There were no trials in which more cars were positioned than had been presented.

Unlike the amounts of positioned cars, the positioning accuracy did decrease as the duration of the distractor task increased (figure 6). However, the effect was not very strong and the inter-trial and the inter-subject variability were high. A significant difference in the average positioning error could only be found between the trials containing a 5s delay and those containing a 30s delay (Wilcoxon signed rank test, p=0.03). Between these conditions the error increased by 20%. The difference between the 1s condition and the 30s condition as well as the difference between 1s condition and the 5s condition did not turn out to be significant (Wilcoxon signed rank test, p=0.1 and p=0.97).

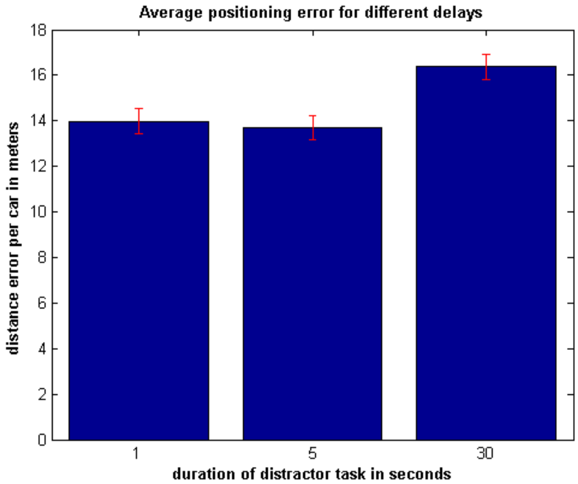

Figure 6: **Mean positioning error plotted versus distractor task duration. Red bars indicate SEMs.**

Closer examination of the data showed that 11 out of 15 subjects performed worse in trials with long delays than in trails with short delays (figure 7). The difference between the 1s condition and the 30s condition and the difference between the 5s condition and the 30s condition were significant for this group (Wilcoxon signed rank test, p=0.003 and p=0.013). However, 4 of the subjects showed no decline in performance or even performed better in trails with long delays (figure 8).

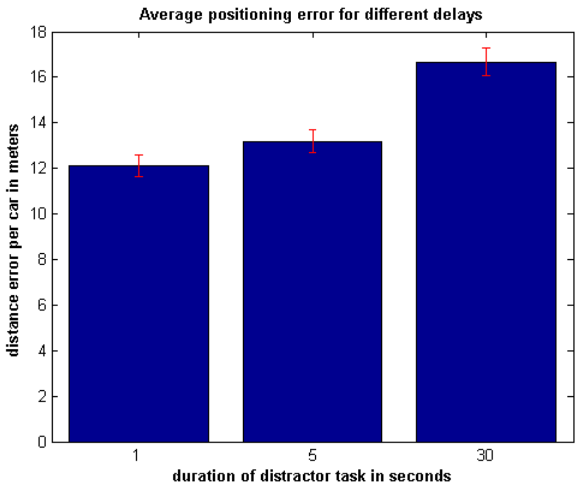

Figure 7: **Mean positioning error plotted versus distractor task duration. Only the 11 subjects who showed a decline in accuracy when the delays were long contribute to the averages. Red bars indicate SEMs.**

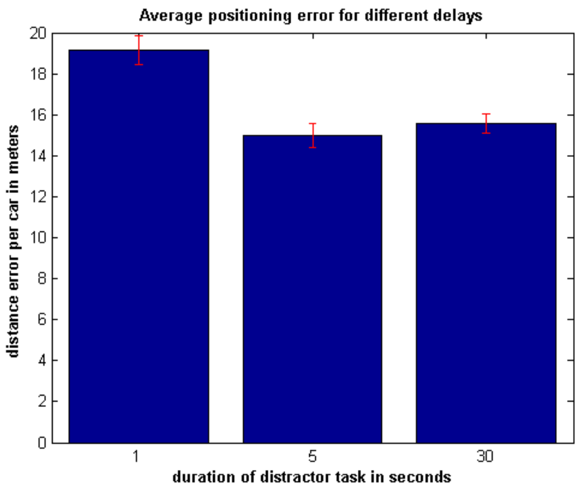

Figure 8: **Mean positioning error plotted versus distractor task duration. Only the 4 subjects who showed stagnation or an increase in accuracy when the delays were long contribute to the averages. Red bars indicate SEMs.**

5 Discussion

The experiment conducted for this study aimed at revealing properties of short-term memory in a collision-avoidance task. Subjects were asked to avoid collisions in a virtual traffic situation. In unpredictable intervals they had to reconstruct the scene they had last observed. Reconstruction was preceded by a delay in which the virtual environment was occluded and subjects had to count loudly. Counting served as a means to suppress articulatory rehearsal.

The results show that subjects are able to retain the traffic situation in memory for as long as 30 seconds despite articulatory suppression. They did not seem to forget cars while they were counting but most of the subjects showed an impairment of reconstruction accuracy. Positioning time was not affected by the delay duration. Furthermore, the reconstructed scenes were dominated by cars which were about to arrive at the intersection subjects needed to cross, indicating that relevance for collision-avoidance correlates with the probability to be encoded in memory.

The observation that subjects remembered roughly four cars on average is in agreement with the capacity limit proposed by Luck and Vogel. As in many previous measurements the variability across subjects was rather high, ranging from 1.2 to 6.2. Assuming that capacity is indeed limited to roughly four objects in static situations, I suggest with precaution that there was no markable reduction of capacity due to movement. However, it is important to note that our paradigm cannot and was not designed to quantify the capacity limit properly. As the analysis shows there is good reason to assume that subjects clustered cars mentally and stored them as a chunk. Cars being part of a spatio-temporal sequence occurred more often in the reconstructed scenes then in random scenes created by a computer program. Thus, subjects tended to recall cars in chunks, suggesting that cars were stored in chunks as well. Some subjects even reported that they had made use of a sequencing strategy. Therefore, the fact that subjects remembered 4.2 cars on average might not reflect the true capacity limit. Indeed, most previous studies estimated the capacity limit to be between 3 and 4, making my estimate appear rather high (Cowan, 2001). The real capacity limit is likely to be somewhat lower and could be estimated more reliably when chunking is minimized. Minimization of chunking could be achieved by using cars of one size only, which would make it much more difficult to build up associations between subgroups of the presented cars.

Forgetting during the distractor task is evidenced by the fact that positioning was significantly less accurate when the distractor task duration was 30s instead of 5s. Performance dropped to 80% between these conditions. The difference between the 1s condition and the 30s condition did become significant only when one excluded the 4 subjects who performed worst when the delay lasted 1s.

It may seem striking that some of the subjects performed worst in the trials with the shortest delay. But given the overall noisiness of the data and the rather small performance differences between the conditions, deviations from the trend do not come unexpected. In particular, clustering is a source of noise. Overestimation of cluster sizes can lead to abrupt increases in the positioning error. For example, placing a row of 4 cars in one region of the street though a row of 3 cars was actually present in that region, usually results in a much bigger error than positioning 3 cars, even when in the former case 3 of the 4 cars match the positions of the presented cars exactly and in the letter case the cars are positioned very inaccurately. The fact that forgetting in our paradigm is partly covered by such noise shows that the advantage of trials with short delays is rather subtle.

In contrast, forgetting in the Brown-Peterson paradigm has been reported to be rapid and pronounced. Performance is said to drop to 10% when delays last 18s. Why did I not find forgetting to a comparable extent? It seems possible that forgetting in this type of paradigm is weaker when the presented material is spatial rather than lexical. Support for this hypothesis comes from a study of Magnussen et al. who presented subjects two gratings with a delay of 10s and asked them to indicate whether the spatial frequencies of the gratings were different. They found that memory stayed perfectly stable within this interval (Magnussen et al., 1991). It is up to future experiments to confirm or reject the difference between the retention of spatial and lexical material.

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