

Dissociating cognitive and motor interference effects on kinesthetic short-term memory

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Abstract In two experiments, we investigated how short-term memory of kinesthetically defined spatial locations suffers from either motor or cognitive distraction. In Exp. 1, 22 blindfolded participants moved a handle with their right hand towards a mechanical stop and back to the start and then reproduced the encoded stop position by a second movement. The retention interval was adjusted to approximately 0 and 8 s. In half of the trials participants had to provide a verbal judgment of the target distance after encoding (cognitive distractor). Analyses of constant and variable errors indicated that the verbal judgments interfered with the motor reproduction only, when the retention interval was long. In Exp. 2, 22 other participants performed the same task but instead of providing verbal distance estimations they performed an additional movement either with their right or left hand during the retention interval. Constant error was affected by the side of the interpolated movement (right vs. left hand) and by the delay interval. The results show that reproduction of kinesthetically encoded spatial locations is affected differently in long- and short-retention intervals by cognitive and motor interference. This suggests that reproduction

behavior is based on distinct codes during immediate vs. delayed recall.

Introduction

When making a movement toward a position in space without visual feedback, only motor-related signals are initially available. How can these signals be used to prepare and execute a movement to the same location after a short time period? Although short-term memory for movements has been extensively studied since 1970s (for early reviews see Laabs & Simmons, 1981; Laszlo, 1992; Smyth, 1984), the knowledge about sensorimotor processes in kinesthetic tasks is still sparse. The results of more recent studies suggest that there are two distinct modes of sensorimotor control. The direct mode, labeled as “pragmatic” (e.g., Jeannerod, Arbib, Rizzolatti, & Sakata, 1995), “sensorimotor” (e.g., Paillard, 1987) or “vision-for-action” (e.g., Goodale & Milner, 1992), is assumed to extract parameters from sensory flow that are primarily relevant for the generation of a corresponding motor behavior. In contrast, the “cognitive” mode (also labeled as “semantic”, “representational”, “vision-for-perception”) enables to build an internal representation by binding stimulus attributes as well as by computing relational metrics of the environmental events. In addition to the functional dissociation (motor behavior vs. perception), several other dichotomies relating to sensitivity, neuronal substrate, speed or consciousness were proposed (e.g., Norman, 2002). Which mechanism is used for movement control seems to depend on the time that passes between encoding of a target and the production of a movement (e.g., Goodale, Westwood, & Milner, 2004; Rossetti & Pisella, 2002). With respect to the kinesthetic modality, Rossetti and Pisella (2002) reported a series of

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pointing experiments in which the delay between a first hand movement (passive displacement) and the reproduction was varied. The authors observed delay-dependent changes in relation to the endpoint distribution: immediate reproduction was associated with a variability ellipse that was oriented in the direction of the pointing movement, while delayed movements (after 8 s) caused ellipses oriented towards other targets (orthogonal to movement direction). Further evidence for a temporal dissociation of the two proposed processing modes in the somatosensory modality is also provided by a neuropsychological case study of Rossetti (1998). A patient with tactile and proprioceptive deficits on the right side of the body as a result of thalamic lesions was able to locate correctly tactile stimuli presented on the right hand by pointing movements with the left index finger. According to his verbal reports he did not perceive the applied stimuli. Similar results were obtained during a kinesthetic task. However, the ability to guide a movement on the basis of unaware somatosensory information was lost, when the stimulus–response interval was extended to a few seconds. Comparable results were obtained with an agnostic patient who lost the ability to correctly reach and grasp objects after 2 s, which she could not describe (Goodale, Jakobson, & Keillor, 1994). Further, the existence of short-living representations, lasting for a few seconds only and to be used for precise sensorimotor transformations is supported by several studies in the visuo-motor area indicating that immediate and delayed actions are controlled differently (Bradshaw & Watt, 2002; Bridgeman, Gemmer, Forsman, & Huemer, 2000; Elliott & Madalena, 1987; Hu, Eagleson, & Goodale, 1999; Vaillancourt & Russell, 2002).

In order to test the hypothesis that the time between encoding and reproduction decides on which representation system is used for reproduction, we conducted two experiments in which we varied the delay in a movement reproduction task. In addition, we tested the effects of verbal-cognitive and motor interpolated activity on reproduction performance. The idea was to characterize the nature of information, which is stored or encoded after movement execution by examining how error measures are affected by these additional tasks in short- and long reproduction intervals. Assuming that an initial kinesthetic representation is maintained for a brief period of time while a more abstract representation of target location is generated for more permanent storage we expected selective impairment of the reproduction task by a cognitive task when the delay is long and by motor task when the delay is short.

Experiment 1

Kinesthetic information of the encoding phase will be used directly for planning the successive movement reproduction

if the delay is short (e.g., Rossetti & Pisella, 2002). Moreover, kinesthetic representations are traditionally assumed to be independent from general attentional capacity that is needed to handle more abstract cognitive representations (see e.g., Laabs, 1973; Posner, 1967; Smyth, 1984). Thus, inserting a cognitive task between encoding and reproduction of a movement should not interfere with reproduction performance when participants have to reproduce a movement immediately. In contrast, with a longer delay a more abstract representation, such as a spatial target location, will be crucial for reproduction. In that case a cognitive task should interact with planning processes of reproduction movements. This prediction follows also from studies showing that location cues are more subject to capacity interference than kinesthetic distance information (see e.g., Diewert, 1975; Laabs, 1973, 1976; see also Laabs & Simons, 1981). For instance, Laabs (1973) demonstrated that the reproduction of terminal locations was strongly influenced by interpolated mental activity (counting backwards in threes and spatial reasoning task), while reproduction of movement extent (distance) was widely unaffected.

We used a one-dimensional positioning task to test this prediction. Participants moved a stylus on a sledge forward until they reached a mechanical stop and then backward to the start position. After a short (0 s) or a longer delay (8 s) an acoustic signal indicated to reproduce this movement. Now the mechanical stop was removed and the participants had to reproduce the encoded end-point of the first movement. In the cognitive interference condition participants had to provide a verbal judgment of the moved distance in cm immediately after finishing the first backward movement. In the control condition, participants just waited until the acoustic signal indicated to start the movement reproduction. We analyzed constant and variable errors as indicators of performance.

Methods

Participants

Twenty-two right handed subjects participated. They gave their informed consent for the procedures and received course credit at the end of the experimental session. Two subjects were excluded from the analyses due to a large number of movement artifacts, which resulted from difficulties in handling the experimental apparatus. The final sample comprised 4 males and 16 females, with ages ranging from 19 to 25 years (mean age 21).

Paradigm and task

The subjects were blindfolded and sat in front of a linear track device, allowing one-dimensional movements of a

pen-like, lightly moveable handle on a horizontal sledge. The movement direction was perpendicular to the coronal plane of the body and the start point was located at the body midline. Eight lift-magnets were mounted in the device in distances between 14 and 35 cm in front of the starting position (3 cm between successive magnets) and were used to stop movements at a specified location. The starting position was defined as the nearest possible handle location in respect to the body (approximately 10 cm). Earphones were used to transmit acoustic signals and to protect against auditory feedback. Before and during the experiment, the subjects were prevented from seeing the apparatus.

A trial started with an auditory warning stimulus, followed after a fixed interval of 3 s by a first imperative go signal (250 Hz). The subjects were asked to move the handle rapidly until the stop and then immediately backward. After the second go signal (250 Hz) participants had to reproduce the stop position as accurately and rapidly as possible with another movement of the same hand. Two delay intervals were used. In a pilot experiment with an equivalent setup response times of the first movement (including reaction times and movement durations of forward and backward movement) lay in the range between 1.2 and 1.5 s. Accordingly, the imperative reproduction signal was presented either 1.5 s after the first signal (immediate reproduction, labeled as delay “0”) or after 9.5 s (delayed reproduction, labeled as delay “8”).

In half of the trials, participants were asked to estimate the movement distance until the stop verbally in cm during the delay interval. In the longer delay condition, an additional auditory signal (1,000 Hz) was presented 4.75 s after the first imperative go signal that indicated to now articulate the distance estimate. In the short-delay condition, judgments were required immediately after the first backward movement.

We used a 2 distractor (control and judgment) \times 8 target locations (stop positions) \times 2 delays (0 and 8) repeated measures design. The experiment was divided into four blocks, each of them comprised 24 trials (8 locations \times 3 repetitions). The delay interval and the type of distractor were held constant within each block (delay 0 and no verbal judgment, delay 8 and no verbal judgment, delay 0 and verbal judgment, delay 8 and verbal judgment). Eight targets were presented randomly with the constraint that the whole sequence of positions should be completed before another repetition. The order of blocks was randomized across participants. Each participant performed four practice blocks, including all conditions.

Data analysis

Movement trajectories of the manipulandum were recorded with an ultrasound motion device (ZEBRIS, CMS 20). The

data were sampled at 100 Hz initially and analyzed with software using Lab View codes (National Instruments, Graphical Programming for Instrumentation).

Constant and variable error measures were defined as dependent variables and analyzed statistically by using repeated measures analyses of variance (ANOVAs) with distractor, target distance, and delay as factors. Constant error score reflects the mean deviation of the moved distance from the target distance and was computed by averaging response errors with the sign of each error being kept. This error is negative when there is a constant undershoot and positive with an overshoot. In order to measure the response consistency independently from the movement amplitude, we calculated a variable error score, i.e., the coefficient of variation [$V = (SD/M) \times 100$], where SD is the standard deviation of the average movement endpoint (M). Due to the small number of repetitions, we pooled two neighboring target positions for this analysis and defined only four levels of factor distance in the ANOVAs.

Systematic verbal errors were computed in the same manner as described for the constant motor errors. The two error types were compared in an ANOVA by means of standardized (z-transformed) values. Delay (0 and 8), distance (8 target locations) and response mode (verbal and motor) were defined as within subject factors for this analysis.

For all analyses, significance was tested on an alpha level of 0.05 and degrees of freedom were adjusted according to Geisser and Greenhouse (1958) when violations of the assumption of sphericity were obtained.¹

Additionally, we investigated the relation between verbal reports and motor responses by computing Pearson's correlation coefficients between the amplitudes of the “encoding” movement and the verbally reported distances. Correlations were also computed between systematic judgment errors and the corresponding motor error values of the reproduction movement. All correlation coefficients were computed on a single trial basis.

Results

Analysis of the variable error revealed highly significant main effects for factors delay [$F(1, 19) = 41.95, p \leq 0.001$] and distance [$F(3, 57) = 59.13, p < 0.001$]. An increase in distance resulted in a decrease of response variability, while the prolongation of the reproduction delay caused an increase of variable error (see Fig. 1). The significant delay \times distractor interaction [$F(1, 19) = 5.50, p = 0.030$] showed that response consistency was

¹ We report uncorrected degrees of freedom and corrected p values in the “Results” section.

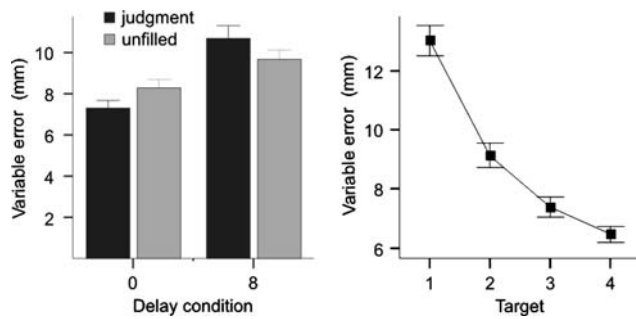


Fig. 1 Exp. 1, variable error. *Left* average variable error scores illustrating the interaction distractor \times delay; *right* average variable error scores for the four target distances (see “Methods”). Error bars indicate standard error

differently affected by the two conditions with or without verbal reports. When the delay interval was long, response variability was larger in the judgment than in the control condition (post hoc test $p = 0.097$). When the delay was short, the effect was reversed, i.e., response variability was larger in the control than in the judgment condition ($p = 0.063$; see Fig. 1, left).

In all conditions, participants overshoot the target distance. An ANOVA of the constant motor error revealed significant main effects for factor delay [$F(1, 19) = 17.45, p = 0.001$] and distance [$F(7, 133) = 22.62, p < 0.001$] and a significant interaction of both [$F(7, 133) = 4.90, p < 0.001$]. Overshooting was larger with shorter distances and decreased with increasing distance. This trend was more pronounced in the long than in the short-delay condition (see Fig. 2).

The reported distance estimates showed that participants were quite accurate to discriminate between the eight target positions. Verbal distance estimates correlated substantially

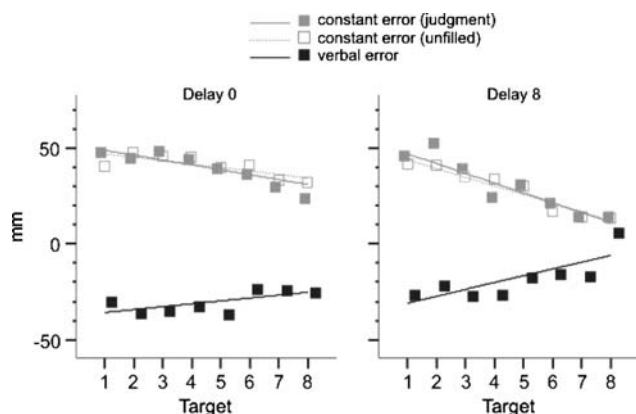


Fig. 2 Exp. 1, average constant motor and judgment errors for the eight target locations and the short- (*left*) and long (*right*) delay condition. Values larger than zero indicate overshoot, values smaller than zero undershoot. Motor error is shown for both conditions, i.e., judgment and control, while judgment error is, of course, only available for the judgment condition

with the distance of the first movement [$r_{\text{delay } 0} = 0.74, r_{\text{delay } 8} = 0.75, \text{ both } p < 0.001$] and proved independent from movement error ($r_{\text{total}} = -0.006, p = 0.866; r_{\text{delay } 0} = 0.03, p = 0.464; r_{\text{delay } 8} = -0.01, p = 0.835$). Nevertheless, verbal judgments showed a systematic underestimation of the objective target position which contrasts with the systematic overshoot revealed by the overt motor responses. In order to quantify the dissociating trends of verbal and motor error we performed an ANOVA with standardized values (z scores) of the dependent variable “error” and independent variables delay (two levels), distance (eight levels) and response mode (two levels: verbal and motor). This analysis revealed significant effects for factor distance [$F(7, 133) = 5.45, p = 0.003$] and for the interactions response mode \times delay [$F(1, 19) = 9.67, p = 0.006$], response mode \times distance [$F(7, 133) = 15.40, p < 0.001$], delay \times distance [$F(7, 133) = 2.53, p = 0.018$] and response mode \times delay \times distance [$F(7, 133) = 2.77, p = 0.010$]. The triple interaction substantiates the trends revealed by Fig. 2, i.e., the dissociation between motor and verbal error decreased with increasing target distance, and this trend of error reduction with increasing distance was more pronounced in the long than in the short-delay condition (see Fig. 2).

Discussion

The main finding of this experiment is that variable motor error, i.e., the consistency with which a certain target location can be reproduced from memory, is differentially influenced by a distracting judgment condition and the delay between encoding and reproduction. Compared with the unfilled control condition, an additional verbal judgment of the encoded distance had adverse effects on variable motor error, if the delay was long, but positive effects if the delay was short. This result provides partial support to the hypothesis that the code used to reproduce a kinesthetically encoded location changes with passing time and that this code is of a more abstract cognitive type, if the time between encoding and reproduction becomes longer than 1 s. In our experiment, it was with a delay of 8 s that variable motor error increased if a verbal judgment had been articulated briefly before. According to the literature on dual task effects accumulated since the important papers (Navon & Gopher, 1979; Norman & Bobrow, 1975) such as selective performance reduction can be taken as a sign that two tasks compete for the same resources. We conclude that the verbal judgment interferes with the representation used for motor planning.

More puzzling is, however, the positive effect of a verbal judgment on variable motor error in the short-delay condition, i.e., if the participant had to reproduce the movement immediately. There is considerable evidence that motor

behavior can profit, if attention is distracted from a motor task, this holds in particular for easy or highly practiced tasks that normally do not draw on attentional resources (Beilock & Carr, 2001; Beilock, Carr, MacMahon, & Starkes, 2002). In such situations, it seems better not to focus attention on the motor task, because the automatized motor programs can then be executed more efficiently and will not be impeded by competing higher-order movement strategies (see also Wulf, McNevin, & Shea, 2001). It was also suggested that the “action” system may be inhibited by a cognitive representation of the action goal (e.g., Rossetti & Pisella, 2002). For example, the motor ability of the patient, mentioned in the “Introduction”, was lost if he was asked to focus attention on it by producing a verbal report simultaneously to the action (Rossetti, 1998; Rossetti, Rode, & Boisson, 1995). For our setup it can be assumed that the overt verbal distance judgments occupied attentional resources and that this might have shielded the fragile kinesthetic code against conscious influences in the short-delay condition indicating a more automatic type of sensorimotor processing. In contrast, the representation used for motor planning in the longer-delay condition seems to depend more directly on attentional resources suggesting a more controlled processing mode.

The second, and somewhat unexpected effect, was the systematic overshoot of the motor performance and the systematic undershoot of the judged distance. Both effects decreased with increasing distance of the target and, moreover, the decreasing trend was more pronounced in the long than in the short-delay condition. Overshooting in kinesthetic tasks has been reported frequently (e.g., Bridgeman et al., 2000; Tillery, Flanders, & Soechting, 1994; Wolpert, Ghahramani, & Jordan, 1995). In our experiment, it is most likely due to the specific experimental setup. Participants were blindfolded and were instructed to perform in the encoding phase a rapid and uncorrected hand movement until they reached a stop and then to reproduce the target location again with a steady, uncorrected second movement. The systematic overshoot with a decreasing trend over increasing distances suggests that participants aimed with their first movement (by default) to a far distance and were more or less abruptly stopped by the mechanical stop. Related results were reported already by Hollingsworth (1909, cf. Granit, 1972) who observed large positive constant errors in a task situation, in which participants moved a carriage along a track on which it was stopped unexpectedly. In this study, the error increased with increasing velocity of the movement and decreased with increasing distance between the locking device and the aimed displacement. The abruptness of the stop is substantiated for our set-up by another study in which kinematic data were measured with the ZEBRIS system (see Kirsch, Hennighausen, & Rösler, 2008). These

data indicate that the motor program for the encoding movement seems to be set to a larger distance than actually needed in most cases. This setting of the movement parameters seems to be preserved for the reproduction movement causing the systematic overshoot that decreased with increasing distance. This seems also to be in line with findings suggesting that joint position estimation is based on an integration of motor command information and sensory feedback signals (Wolpert et al., 1995). This would also explain the unusual decrease in response variability with target distance, which may indicate changes in the quality of the final position estimation as a consequence of the mentioned conflict.²

In contrast, the systematic undershoot of the judgments seems to imply a compensation of the perceived movement error. This effect reminds of the size-weight illusion (SWI) that has been explained as a mismatch between visual and kinesthetic input (Granit, 1972; Jones, 1986; Murray, Ellis, Bandomir, & Ross, 1999). If two objects have the same weight but a different size (volume) the larger object is expected to be heavier than the smaller and vice versa, and accordingly the larger object is lifted with more force than the smaller. The discrepancy between predicted and actual sensory information is assumed to cause a perceptual bias (i.e., the SWI). Our experimental setup resembles the typical SWI paradigm in some respects (see above) and therefore, may have caused a similar mismatch between expected and actually perceived information. Moreover, recent studies suggest that the conflict between predicted and actual sensory information may differ for perceptual and motor control processes. Flanagan and Beltzner (2000), e.g., observed that after a few trials participants adjusted the applied force to the actual weight of objects while the SWI nevertheless persisted until the end of the experiment (see also Grandy & Westwood, 2006 for similar results). Accordingly, it was concluded that distinct mechanisms are utilized by the perceptual/cognitive and sensorimotor systems for determining object mass. The opposite trend of verbal estimations and motor performance observed in the present study is in line with the findings on the SWI and suggests that perceptual and sensorimotor mechanisms may bias the performance in opposite directions under certain task conditions.

In sum, both findings provide support to the hypothesis that maintenance and/or planning processes which guide a reproduction movement change over time. These changes may be associated with the use of different information

² In similar experimental setups, we found that also the standard deviation, i.e. a measure not relativized to the mean amplitude, did not reflect the typically observed increase in variability with distance. In contrast, the pattern resembled the reported result, i.e. increasing distance was associated with a decrease in response variability (see Kirsch et al., 2008).

sources (e.g., intrinsic vs. extrinsic) and/or with different processing modes (e.g., sensorimotor vs. cognitive). Moreover, the results suggest that despite initially identical input explicit judgments and motor planning may rely on distinct mechanisms.

Experiment 2

The first experiment had shown that an additional cognitive task (distance judgment) selectively interfered with the reproduction of kinesthetically encoded movements: reproduction performance was impaired by the cognitive task when the delay interval was long and improved when it was short. For the detrimental effect in the long-delay interval, we argued that in this case movement reproduction is based on a more extrinsic source of information, such as the target location in space, and that this representation shares cognitive resources with information used for the explicit distance judgment. Therefore, motor performance suffers from kind of a resource conflict. For the short-delay condition, we argued that the initial kinesthetic trace of the encoding movement is shielded against cognitive influences, if attentional resources are captured by another task immediately after encoding. With Exp. 2, we wanted to show that there is also the opposite effect, i.e., the kinesthetic code assumed to be relevant for motor performance in the short-delay condition should be selectively disturbed by means of another task that relies on kinesthetic representations too.

Studies, which tested how interpolated kinesthetic activity affects location vs. distance reproduction revealed that both reproduction modes can be selectively affected by a motor distractor but in different ways (Hagman, 1978; Laabs, 1974). The distance of the interpolated activity proved to be critical for distance reproduction, while the end locations of the distractor movements affected primarily location reproduction (see also Laabs & Simmons, 1981; Smyth, 1984). For our linear positioning task, we assume that in the short-delay condition participants primarily reproduce the distance by using dynamic kinesthetic information and that in the long-delay condition they reproduce locations by using more abstract spatial coordinates. Therefore, we expect that another interpolated movement should primarily interfere with the reproduction performance in the short-delay condition.

Moreover, initial somatosensory information is assumed to be effector-specific (e.g., Soechting & Flanders, 1992). Harris, Harris and Diamond (2001), e.g., reported a series of experiments, in which vibration stimuli were applied to different fingertips, on the same or on the opposite hand, and frequency comparisons were required. The authors observed that with short retention intervals (<1 s) the

judgments were most precise, when the same finger was stimulated. With longer-delay intervals performance proved to be independent from whether the same or the corresponding finger of the opposite hand was stimulated. Finally, when the retention interval was 1 s, accuracy decreased when the distance between the vibration sites on the same hand increased (i.e., distance between the first stimulated finger and a neighboring finger stimulated after a delay). Again, this correlation vanished when the delay interval was 2 s. The authors argued that, dependent on delay duration, the somatosensory cortex of the two hemispheres might be differently involved in tactile short-term memory and suggested that retention in the short-delay conditions (<1 s) is independent from a cross-talk between hemispheres while with longer retention intervals tactile representations rely on mechanisms involving both hemispheres.

We took these observations as a starting point and inserted another movement between encoding and reproduction of the linear positioning movement. This additional movement had to be performed either with the same (right) hand as the primary reproduction task or with the left hand. We predicted that in the short-delay condition interpolated movements should interfere more with reproduction performance than in the long-delay condition. Moreover, we expected an interaction between the side of the interpolated movement (left or right) and the length of the delay interval (short, long), i.e., the reproduction movement should be affected more in the short-delay interval with a right than a left hand interpolated movement. No such effect was expected for the long-delay interval.

Methods

Participants

Twenty-two right handed students of the University of Marburg, who did not participate in Exp. 1, were recruited and compensated with course credit. Due to an insufficient quality of data, one participant had to be excluded from the analyses. The remaining participants were 16 females and 5 males between 18 and 35 years of age (mean age 22). All individuals gave their informed consent prior to the experiment.

Paradigm and task

The same apparatus and setup was used as in Exp. 1, but instead of verbal judgments (and unfilled conditions), the subjects were asked to perform a short interpolated movement of 10 cm length with their left or right hand in each trial during the delay. This second movement had to be performed immediately after the encoding movement in

the short-delay condition, and on command of another acoustic signal after 4.75 s in the long-delay condition. The experiment had again four blocks: delay 0 and right hand, delay 8 and right hand, delay 0 and left hand and delay 8 and left hand. Before each block the subjects were informed about the delay duration (short or long) and the type of the interpolated movement (left hand or right hand). All other manipulations were as in the first experiment.

Data analysis

Data recording and preprocessing were done as described in Exp. 1. Constant and variable error measures were used as dependent variables and ANOVAs were calculated with the within-subjects factors delay (two levels), target distance (8/4 levels) and distractor (intermediate movement: left vs. right hand) for statistical analyses.

Additionally, we compared the amplitude of the intermediate movements across experimental conditions by using another ANOVA with the same factors.

In order to investigate the relation between the amplitude of the “encoding” and intermediate movements, we computed Spearman’s correlation coefficients between the target distance and the amplitude of the intermediate movements.

Results

Experiment 2 replicated several effects already observed in Exp. 1. First, ANOVA of the variable error revealed again significant main effects of delay [$F(1, 20) = 21.66, p < 0.001$] and of distance [$F(3, 60) = 42.59, p < 0.001$]. As in Exp. 1, response variability decreased with increasing movement distance and was larger in the long than in the short-delay condition (see Fig. 3).

Second, ANOVA of the constant error showed three significant effects replicating findings from Exp. 1: These are main effects distance [$F(7, 140) = 8.50, p < 0.001$]

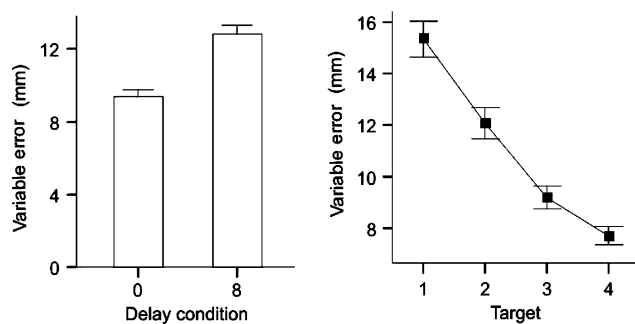


Fig. 3 Exp. 2, variable error. *Left* average variable error scores for the two delay conditions; *right* average variable error scores for the four target distances (see “Methods”). Error bars indicate standard error

and delay [$F(1, 20) = 35.17, p < 0.001$] and the interaction, delay \times distance [$F(7, 140) = 3.56, p = 0.007$]. These effects show again that participants overshoot systematically the target distance, that this bias decreased with increasing movement distance, and that the decreasing trend of overshooting with increasing distance was much more prominent in the long than in the short-delay condition (see Fig. 4, right).

New and specific to the manipulations introduced in Exp. 2 is another effect revealed by the ANOVA of constant error, viz. the interaction delay \times distractor [$F(1, 20) = 4.91, p = 0.039$]. As can be seen in Fig. 4 (left) reproduction performance was significantly more biased in the short than in the long-delay condition, but in addition, in the short-delay condition the overshooting error was larger when the intermediate movement was executed with the left than with the right hand (post hoc contrast $p = 0.071$), while in the long-delay condition the trend was reversed, i.e., overshooting was larger with a right hand than with a left hand interpolated movement (post hoc $p = 0.078$).

We also analyzed the length of the interpolated movement. Although participants had been instructed to always perform an interpolated movement with the same length of about 10 cm the actual length of this movement varied systematically (see Fig. 5). The corresponding ANOVA revealed highly significant main effects of factors delay [$F(1, 20) = 32.15, p < 0.001$], distractor [$F(1, 20) = 35.95, p < 0.001$] and distance [$F(7, 140) = 54.13, p < 0.001$] and a significant triple interaction delay \times distance \times distractor [$F(7, 140) = 2.82, p = 0.009$]. In short, the interpolated movement length was larger with a long than with a short delay, it was larger when it was executed with the right hand (i.e., the same hand as the positioning movement), and it increased monotonously with increasing length of the encoded movement. Compared to these three main effects the triple interaction explains much less variance. As can be seen in Fig. 5, it seems to be mainly due to

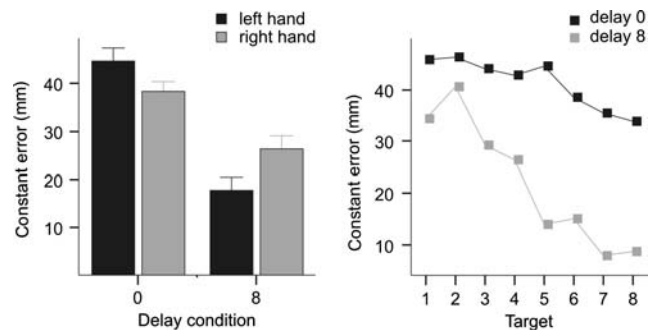


Fig. 4 Exp. 2. *Left* average constant motor error scores illustrating the interaction distractor \times delay and the main effect delay; *right* average constant motor error scores illustrating the interaction delay \times distance

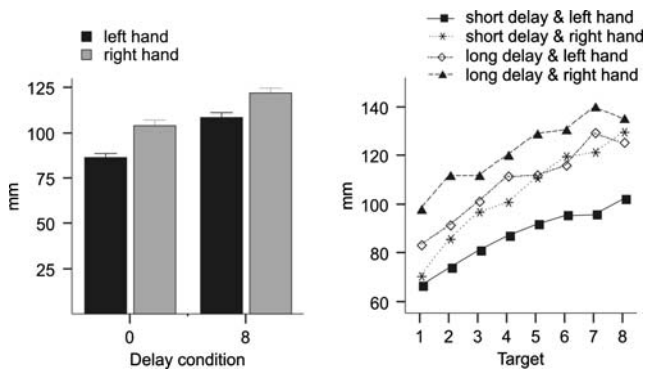


Fig. 5 Exp. 2. *Left* mean amplitude of the distractor movements as a function of side of distractor movement and delay; *right* mean values of all experimental conditions illustrating the triple interaction delay \times distractor \times distance

unsystematic fluctuations of the trend over distance in the four condition combinations.

In order to clarify the interdependencies of the encoding and the interpolated movement we correlated the length of the first (“encoding”) and the length of interpolated movement on a single trial basis. In all four, delay \times distractor conditions these correlations were positive and highly significant ($p < 0.01$), ranging from 0.32 to 0.45. The average correlation amounted to 0.39, i.e., there was a systematic assimilation effect: a longer movement during encoding induced a longer path of the interpolated movement.

Discussion

The main finding of Exp. 2 was the interactive influence of factors delay and side of interpolated movement on the constant motor error. With a short delay, i.e., an immediate reproduction of the encoded movement, participants overshoot the target systematically but this overshoot was larger with a left than with a right hand interpolated movement. In contrast, with a long delay, the overshooting was overall smaller than in the short-delay condition, but the bias was then larger with a right than with a left hand interpolated movement. A general, delay-dependent overshoot had also been observed in Exp. 1. There, we had argued that participants aimed by default to far goal and, therefore, overestimated most of the short and intermediate locations. The question that has to be answered now is why this bias is differently influenced by a left or a right hand interpolating movement when the delay was short or long.

We argued that in the short-delay condition the reproduction movement is based primarily on kinesthetic information that must be a mélange of the initial default motor program started in the encoding epoch and the feedback provided by the mechanical stop. Because of this

it is reasonable to assume that an interpolated movement will interact with the kinesthetic code used for reproduction more when it is executed with the same hand rather than when it is executed with the other hand. Since the interpolated movement should aim at a relatively short distance (10 cm), which is smaller than the majority of the targets, it is likely that this activity with the same hand interferes with the original memory trace. Thus, the obtained decrease in overestimation in the right hand condition as compared with the left hand condition may reflect stronger assimilation effects, which were often obtained in several early motor memory studies (Laabs & Simmons, 1981) and consequently, stronger interference processes. When the interpolated movement is executed with the left hand, however, such an “overwriting” of the initial representation will occur to a much lesser extent, if at all. In sum, we argue that the motor program used for reproduction in the short-delay condition is erased more when an interpolated movement has to be performed with the same hand as used for reproduction than when it is performed with the opposite hand.

In order to understand the reverse effect in the long-delay condition one has to briefly recapitulate the experimental setup. Participants performed the first encoding movement, then, they waited for about 4 s, performed the interpolated movement, waited another 4 s, and finally performed the reproduction movement. We have argued above that the kinesthetic representation that is available immediately after encoding will gradually fade out and be replaced by a more abstract representation. This fading will be undisturbed if the interpolated movement is performed with the opposite (left) hand, because kinesthetic representations can be assumed to be effector-specific. If, however, the interpolated movement is performed with the same (right) hand the new movement will kind of refresh the kinesthetic representation, and, therefore, the original motor program will have a longer lasting impact on the reproduction movement.

The analysis of the length of the interpolated movements gives support to this idea that an assimilation of encoded (memorized) and interpolated movement takes place (see also Laabs & Simmons, 1981). The interpolated movement increases successively with increasing distance of the encoded target from the starting position. This agrees with earlier findings, e.g., of Trumbo, Milone, and Noble (1972) and it reveals a systematic carry-over effect from the encoded movement representation to the interpolated movement. Interestingly, in both delay conditions this carry-over effect is stronger when a right hand interpolated movement has to be performed, i.e., a movement with the same hand, as used for encoding (and reproduction). In the course of our argument this has to be expected, because the influence of the kinesthetic representation prevailing after

encoding must be stronger when the same hand is moved again rather than when the other hand—that was just resting before—is moved.

These conclusions agree with findings of early motor memory studies, which showed that static location cues are superior to dynamic distance information cues, when movement goals have to be retained over a delay of seconds. It is also in line with findings that indicate distinct effects of dynamic and static interpolation cues on the reproduction of distances and locations, respectively (see e.g., Smyth, 1984). The results seem to contradict, however, the assumption that a “pure” effector-specific representation is used in the short-delay condition, because carry-over effects from the encoded movement to the interpolated movement are also detected when the left hand was used for the interpolated task.

General discussion

The objective of the present study was to investigate whether the reproduction of a kinesthetically encoded spatial location relies on different types of representations when the retention interval is either short (≤ 1 s) or long (> 1 s). To this end we varied the duration of the retention interval and, in order to selectively interfere with the one or the other code we introduced two distinct types of intervening activities between encoding and reproduction, a cognitive judgment task and another motor task. The data provided several pieces of evidence supporting the idea that the code used for reproduction does indeed change over time. When a movement is reproduced immediately it seems to rely more on a direct kinesthetic code, which is then replaced by a more abstract representation of the target location in space. Evidence for such a change was provided by selective interaction effects that the two distracting tasks (cognitive, motor) and the retention interval (short, long) exerted on variable and constant error measurements. Although the observed effects reconcile with the interpretation of distinct codes, the actual pattern of results proved to be rather complex suggesting not an “either–or” of the two available codes but rather a gradual dominance of the one or the other. Moreover, the effects were at least in part counterintuitive in that an interacting interpolated activity had not only detrimental but also sometimes beneficial effects on motor performance in the one or the other condition. These contradictory effects could be explained by a subtle analysis of the experimental setup and by considering further factors of influence as shift of attentional focus or the mutual influence of the encoding movement on the intervening activity (judgment or second movement) and vice versa. Moreover, besides the delay-dependent interaction between verbal reports and

movement variability, the verbal distance estimations were affected by the target distance in an opposite manner as compared with the movement amplitude. This suggests a mismatch between distinct information domains as discussed for the size–weight illusion.

These interpretations are, of course tentative and have to be substantiated in further studies. Nevertheless, some other observations, such as of the interaction between delay and target distance in constant errors, which were replicated across the two experiments, seem to confirm the main conclusion of qualitative changes in processing with delay.

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