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TEMPORAL ACCURACY OF MENTALLY SIMULATED TRANSPORT MOVEMENTS[1]

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Summary.—Several studies have indicated a clear correspondence in the durations of active versus mentally simulated actions. The present study examined whether this would also be found when a new and unfamiliar task (the pedalo) was given to 15 sports students aged 21 to 27 years, and the range of mental simulation was extended to cover two different modalities. Despite several modifications of experimental procedure, results always showed high correlations between actual and mental durations similar to those reported for walking by Decety, Jeannerod, and Prablanc in 1989. There were also higher scores on absolute error. However, there were no significant differences between mental simulations with open versus closed eyes. It is concluded that the timing of the execution and mental simulation of closed and cyclical movements is interrelated and based on common mechanisms.

Different methodological approaches are used to investigate the imagery of action and movement. One paradigm focuses on subjective and private phenomena related to imagery. Participants are often asked to scale the vividness of their own imagery or their control over it. Well-known examples are the Movement Imagery Questionnaire (Hall, Pongrac, & Buckolz, 1985; Hall & Martin, 1997) and the Vividness of Movement Imagery Questionnaire (Isaac, Marks, & Russell, 1986). A second paradigm confronts participants with tasks requiring mental transformations. This paradigm infers internal processes from objective characteristics of a task. In fact, it is even possible for a participant to exhibit optimal performance on the relevant task without being aware of any mental imagery. One example of this "objective" strategy is Shepard and Metzler's mental rotation tasks (1971).

These otherwise mutually exclusive strategies converge in studies on the temporal accuracy of movement imagery. Experimental procedures start off with subjective reports on the beginning and end of mental transformations but then go on to apply objective experimental methods. They can also measure the timing of neurophysiological correlates such as electroencephalography (EEG). Such an approach combines the advantages of both strategies.

Knowledge of the temporal accuracy of dynamic images is of fundamental importance for mental training procedures in sport. It is often postulated that top athletes have better representations of the temporal characteristics

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of their actions at their disposal than athletes of average ability (Beier, 1978). Three recent studies on golf (Orliaguet & Coello, 1998) and badminton (Munzert & Möllmann, 1997; Munzert, unpublished data) did not confirm this hypothesis. However, there are only a few studies on the mental chronometry of movement imagery that address mental training procedures.

Neuroscientific studies on mental chronometry reveal a controversy regarding the strength of the relationship between motor programs and movement imagery. According to Annett (1996), there are two classes of theories emphasizing either the symbolic content of imagery or the identity of the motor program and the motor image. Jeannerod's concept (1994) favors the latter view. He considers that movement images are generated by activation and later inhibition of the motor program. For a long time it was unclear whether the primary motor cortex is also involved in motor imagery, and it is only recently that studies have confirmed this (Leonardo, Fieldman, Sadato, Campbell, Ibanez, Cohen, Deiber, Jezzard, Pons, Turner, Le Bihan, & Hallett, 1995; Roth, Decety, Raybaudi, Massarelli, Delon-Martin, Segebarth, Morand, Gemignani, Decorps, & Jeannerod, 1996; Pfurtscheller & Neuper, 1997). Results on the temporal concordance of actual and imagined movements have delivered strong support for Jeannerod's concept of movement imagery.

Decety, Jeannerod, and Prablanc (1989) have reported a basic experiment with an elegant design. Participants either had to walk different distances blindfolded or imagine walking them. Results showed an almost perfect correspondence between mental and actual durations. In the second part of the experiment, participants had to carry or imagine they were carrying a 25-kg weight. The additional weight influenced mental but not actual walking times.

Similar timing accuracy in mental simulations has been found for writing and drawing movements (Decety & Michel, 1989). Decety and Jeannerod (1996) demonstrated that task difficulty (conceptualized in terms of Fitt's Law) affects actual and mental durations in the same way. Further evidence also comes from the rehabilitation domain. Sirigu, Cohen, Duhamel, Pillon, Dubois, Agid, and Pierrot-Deseilligny (1995) have reported the case of a patient with unilateral damage to the motor cortex resulting in a slowing of contralateral movements. Clinical examinations yielded a corresponding slowing of the imagined speed of the affected but not the unaffected hand. Similar phenomena have been observed in patients with early stages of Parkinson's disease resulting in unilateral forms of akinesia (Dominey, Decety, Broussolle, Chazot, & Jeannerod, 1995) and in patients with right hemiplegia (Decety & Boisson, 1990). In all studies, a selective slowing of the affected movement and of the corresponding mental transformations could be observed.

The present study examined whether the temporal correspondence between actual and imagined durations also generalizes to other "closed skills". Performance on a pedalo was selected for the task. Pedalos (see Fig. 1) are usually used for training children with mild retardation in motor development. Similar to the walking task, they require cyclical movements. During early learning stages, participants often feel they should step on the boards vertically to move the pedalo forward; in later learning stages, they usually report pushing the boards in a more horizontal direction (Körndle, 1983; Zimmer & Körndle, 1988). The rolling movements are dampened only slightly, resulting in relatively strong tactile and kinesthetic feedback. Compared with Decety, *et al.*'s walking task (1989), the present pedalo task is a cyclical transport movement (rolling) with enhanced balance requirements and more tactile and kinesthetic sensations. The latter may be a consequence of the participants' complete lack of familiarity with the task.

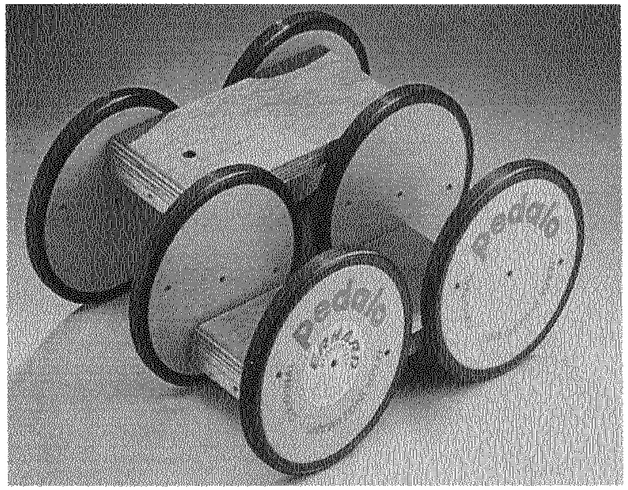

FIG. 1. The pedalo. (Reprinted with permission from Erhard Sport International)

Unlike Decety, *et al.* (1989), the present study did not repeat distance conditions. Distances changed randomly from one trial to the next. Alongside the blind and mental conditions, two further conditions were introduced. First, it seemed necessary to introduce a condition with normal vision to serve as a baseline. In addition, two different mental conditions were applied. Without specific instructions, participants often close their eyes during mental rehearsal. Although this enables them to avoid interference between imagery and ongoing vision, it also leads to additional requirements regarding the imagery of spatial proportions, especially imaging the correct distance. Mental imagery of movements with eyes open removes the need for these additional processes. Functional similar processes are activated, but they are based on different sources of input, information which arises from immediate input from the eyes or from stored memory (Kosslyn, 1994). Therefore, the present study also analyzed variation in mental rehearsal (eyes open vs eyes closed).

Method

Participants

Fifteen participants, all sport students at the University of Giessen, took part in the experiment. Their ages ranged from 21 to 27 years ($M=24.2$, $SD=1.6$). The Vividness of Movement Imagery Questionnaire (Isaac, *et al.*, 1986) indicated that they possessed good imagery abilities with a mean score of 1.9 ($SD=0.5$) for imagining oneself and a mean of 2.1 ($SD=0.5$) for imagining another person. The Gordon Test (Richardson, 1969) produced a mean score of 7.1 ($SD=4.3$). This scale measures the ability to control imagery. Participants also showed good ability for imagery ($M=14.3$, $SD=3.7$) on an objective test of mental transformations, which required judgements about mirror images (a subtest of the Wilde-Intelligence-Test; Jäger & Althoff, 1994). None of the participants had prior experience with the task.

Task and Procedure

To familiarize themselves with the task, participants practiced for 5 min. with the pedalo (Erhard Sport International, POB1163, 91533 Rothenburg o.d.T., Germany). No instructions and no feedback were given. In Exp. 1, participants then attempted five distances (3 m, 6 m, 9 m, 12 m, 15 m) under three conditions (Active/eyes open, Mental/eyes open, Mental/eyes closed). Exp. 2, which was run 14 days after Exp. 1, repeated the procedure for the conditions Active/eyes closed, Mental/eyes open, and Mental/eyes closed. All participants participated in both experiments. Within experiments, the order of distances and conditions was randomized in such a way that no distance and no condition was repeated. As a result, each of the 15 trials in Exps. 1 and 2 (5 distances × 3 conditions) was performed once. Participants were instructed to work at a comfortable speed and took about 30 minutes to complete the tasks in each experiment.

They were asked to observe the actual distance for 5 sec. These distances were marked with a cone similar to those used in sports or road safety training. Then, they had to imagine the same distance for a further 5 sec. Decety, *et al.* (1989) have reported that this instruction to perform a mental rehearsal of distances has a positive effect on timing accuracy. In Active conditions, participants moved the pedalo; in Mental conditions, they gave verbal reports on the start and end of their mental simulation. Participants were instructed not to estimate time intervals but to report the course of their images.

Data Collection and Data Analysis

The experimenter used a stopwatch to measure active and mental durations. In the condition Active/eyes closed in Exp. 2, the distance was read from a tape beneath the participant's track.

Dependent variables were absolute durations as well as absolute and constant errors of duration. Error calculation in Exp. 1 refers to the Active/eyes open condition, whereas in Exp. 2 the Active/eyes closed condition serves as a baseline. Only error calculation in Exp. 2 corresponds with that of Decety, *et al.* (1989), who used an Active/eyes closed but no Active/eyes open condition in their experiment. For better illustration, absolute error of duration was transformed into percentage absolute error. This error measure takes individual differences in absolute durations into account. For the condition Active/eyes closed, absolute and constant error of distance were measured. Mean speeds were calculated for both Active conditions and for Mental/eyes open. Each experiment had a 5 (distance) × 3 (conditions) design with repeated measures on both variables.

Results

Duration of Actual and Mental Trials

Table 1 reports mean actual and mental durations for all distances and conditions. The first step was to analyze durations in the first experiment (pedalo with eyes open). A 3 × 5 analysis of variance indicated significant effects for Conditions ($F_{2,28}=3.86$, $p<.05$, $\eta^2=.22$), Distances ($F_{4,56}=66.08$, $p<.001$, $\eta^2=.825$), and for their interaction ($F_{8,112}=2.39$, $p<.05$, $\eta^2=.15$). Separate comparisons among conditions identified only significant differences between Mental/eyes open and Mental/eyes closed ($F_{1,14}=20.48$, $p<.001$, $\eta^2=.59$). Table 1 shows that this was due to longer mental durations in the Mental/eyes closed trials. *Post hoc* analyses of single distances showed that only the 12-m distance differed significantly between the conditions ($t_{14}=5.56$, $p<.001$). Duration of the Mental/eyes closed condition was 4.3 sec. longer than the Mental/eyes open condition. For the 15-m distance, the difference between conditions was not significant ($t_{14}=1.83$, $p=.09$), with a difference between conditions of 3.1 sec.

The same analyses were repeated for Exp. 2. A 3 × 5 analysis of variance yielded no significant effect for Conditions ($F_{2,28}=.44$, ns, $\eta^2=.03$), a

TABLE 1
MEAN ABSOLUTE DURATIONS FOR ACTIVE AND MENTAL TRIALS IN BOTH EXPERIMENTS

Distance	Experiment 1						Experiment 2					
	Active/ Eyes Open		Mental/ Eyes Open		Mental/ Eyes Closed		Active/ Eyes Closed		Mental/ Eyes Open		Mental/ Eyes Closed	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
3 m	5.8	2.1	7.1	3.2	7.0	2.6	6.4	2.9	7.2	3.3	7.4	2.8
6 m	11.5	4.3	12.9	6.1	14.3	7.6	13.9	5.0	15.1	8.8	15.0	6.8
9 m	17.3	6.3	18.2	8.6	18.1	7.7	21.7	7.6	20.0	10.0	19.6	7.9
12 m	22.2	8.5	21.5	11.5	25.9	12.4	28.8	11.1	26.9	13.0	27.4	12.7
15 m	28.0	11.5	26.3	12.6	29.3	13.5	33.5	13.7	32.8	16.0	31.3	15.9

significant effect for Distances ($F_{4,56}=68.08$, $p<.001$, $\eta^2=.83$), and no effect for their interaction ($F_{8,112}=1.19$, $p<.31$, $\eta^2=.08$). Unlike Exp. 1, there was no significant difference between Mental conditions ($F_{1,14}=0.20$, $p=.66$, $\eta^2=.01$), and no significant interaction ($F_{4,56}=0.59$, ns, $\eta^2=.04$).

In summary, there were only small differences between conditions. These were somewhat larger in Exp. 1. These differences between Mental conditions in Exp. 1 (and for longer distances) could not be replicated in Exp. 2.

Absolute Error of Mental Duration

Because inspection of the data in Table 1 indicated no systematic tendency for mental durations to be too short or too long, absolute error (AE) was chosen as the unit of analysis. Table 2 reports mean absolute errors for distances and conditions.

TABLE 2
MEAN ABSOLUTE ERROR IN DURATION OF MENTAL TRIALS

Distance	Experiment 1				Experiment 2			
	Eyes Open		Eyes Closed		Eyes Open		Eyes Closed	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
3 m	1.6	1.3	1.8	1.3	1.4	1.3	1.2	1.0
6 m	2.6	1.9	3.0	4.3	3.3	4.5	2.7	2.5
9 m	2.9	3.0	2.7	2.2	3.8	3.0	3.2	3.4
12 m	4.4	2.8	4.7	4.8	3.3	2.2	2.9	2.4
15 m	6.5	4.2	5.8	4.7	7.4	5.1	8.6	7.9

Absolute error was analyzed by computing a 2 (Experiments) × 2 (Mental condition) × 5 (Distances) analysis of variance with repeated measures on all three variables. Once again, there was a significant effect for Distance ($F_{4,56}=11.92$, $p<.001$, $\eta^2=.46$), but no significant effects between experiments ($F_{1,14}=0.12$, ns, $\eta^2=.008$) or between Mental conditions ($F_{1,14}=0.90$, ns, $\eta^2=.006$). Only the two-way interaction between Distances and Experiment interestingly fell just short of statistical significance ($F_{4,56}=2.26$, $p=.075$, $\eta^2=.14$; all other interactions were nonsignificant). Single comparisons gave no statistical effect ($-1.27<t_{14}<0.63$, ns) between Mental conditions for single distances.

Mean percentage absolute error was calculated for ease of illustration. In Exp. 1, percentage absolute error was 22.5% (*SD*=11.1%) for Mental/eyes open and 23.7% (*SD*=20.0%) for Mental/eyes closed. In Exp. 2, these values were 21.7% (*SD*=11.8%) and 21.0% (*SD*=12.1%), respectively.

Error for Distance

Exp. 2 contained Active trials with no visual control (Active/eyes closed). As a result, errors for distance estimation could be anticipated. Table 3 reports mean absolute and mean constant errors for distances. Negative constant error values indicate that the mean distances were too short. Analyses of variance with repeated measures for distance yielded no significant effect for constant error ($F_{4,56}=1.37$, ns, $\eta^2=.09$), but a significant effect for absolute error ($F_{4,56}=5.04$, $p<.01$, $\eta^2=.27$).

TABLE 3
MEAN ABSOLUTE ERROR AND MEAN CONSTANT ERROR FOR DISTANCES IN ACTIVE/EYES CLOSED CONDITION

Error	3 m		6 m		9 m		12 m		15 m	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Constant	–0.3	0.5	–0.2	1.0	–0.1	1.8	–0.9	1.8	–0.7	2.3
Absolute	0.4	0.4	0.8	0.7	1.2	1.3	1.4	1.4	1.7	1.6

Analysis of Speed

Given individual differences in actual distances for the Active/eyes closed condition, it seemed worthwhile to perform further analyses of speed. Speed may well act as a subjective indicator for timing processes. Whereas the variable "speed" can be computed for the conditions Active/eyes open, Active/eyes closed, and Mental/eyes open, the exact distance of the simulated trials cannot be ascertained for the condition Mental/eyes closed. Table 4 reports mean velocities for conditions and distances.

Speed data were analyzed with a 2 (Active vs Mental) × 2 (Experiment) × 5 (Distance) analysis of variance with repeated measures on all variables. There was a significant effect of Experiment ($F_{1,14}=7.65$, $p<.05$, $\eta^2=.35$), which could be traced back to higher speed in Exp. 1, and for Distance ($F_{4,56}=8.67$, $p<.001$, $\eta^2=.38$), resulting from higher speed on longer distances, but no relevant effect for conditions (Active vs Mental) ($F_{1,14}=0.63$, ns, $\eta^2=.04$). There were significant two-way interactions for Experiment and Distance ($F_{4,56}=3.25$, $p<.05$, $\eta^2=.19$) and for Conditions and Distance ($F_{4,56}=5.01$, $p<.01$, $\eta^2=.26$). However, neither the two-way interaction be-

TABLE 4
MEAN SPEEDS FOR CONDITIONS AND DISTANCES (IN M/SEC.)

Distance	Experiment 1				Experiment 2			
	Active/ Eyes Open		Mental/ Eyes Open		Active/ Eyes Closed		Mental/ Eyes Open	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
3 m	0.58	0.23	0.51	0.21	0.51	0.28	0.50	0.21
6 m	0.61	0.27	0.58	0.29	0.47	0.22	0.50	0.21
9 m	0.60	0.26	0.60	0.26	0.47	0.21	0.55	0.25
12 m	0.63	0.27	0.69	0.30	0.44	0.19	0.55	0.25
15 m	0.64	0.29	0.71	0.36	0.52	0.32	0.56	0.25

tween Experiment and Condition ($F_{4,56}=1.07$, ns, $\eta^2=.07$) nor the three-way interaction attained significance ($F_{4,56}=0.74$, ns, $\eta^2=.05$). The significant interaction between Experiment and Distance resulted from higher speeds over longer distances in Exp. 1. The significant interaction between Condition and Distance was due to higher speeds in the mental simulation of longer distances.

Intercorrelations for Time and Speed

Correlational time data between conditions was calculated for each distance separately. The resulting coefficients (5 distances × 3 correlations) were $.68<r<.98$ ($p<.01$) for Exp. 1 and $.70<r<.97$ ($p<.01$) for Exp. 2. For further analyses, mean correlational coefficients for Conditions were calculated on the basis of Fisher's *Z* transformation. The resulting values were $.87<r<.92$. In summary, there were very high correlations between conditions in both experiments. Coefficients were similar to those reported by Decety, *et al.* (1989).

The same procedure was repeated for speed data. In this case, the data from both experiments were combined. Mean correlations (based on Fisher's *Z* transformation) are reported in Table 5. All correlation coefficients were quite high with the exception of that between Mental (Exp. 1) and Active/eyes closed (Exp. 2). Correlation coefficients for speed were lower than those for time. This made it necessary to reject the hypothesis that speed would provide a better time representation.

TABLE 5
MEAN PEARSON PRODUCT-MOMENT CORRELATIONS OF SPEEDS IN EXPS. 1 AND 2

Condition	Experiment 1	Experiment 2	
	Mental/Eyes Open	Active/Eyes Closed	Mental/Eyes Open
Experiment 1			
Active/Eyes Open	.79	.72	.86
Mental/Eyes Open		.42	.74
Experiment 2			
Active/Eyes Closed			.69

DISCUSSION

In line with the original experiments of Decety, *et al.* (1989), we have found further support for a strong correspondence between mental and actual durations. This can now be generalized to an unfamiliar cyclical motor task like the pedalo. The correlational data provide particularly strong support for the hypothesis of a good fit. Mean correlations between actual and mental durations range from .86 to .93. Additionally there are no significant differences between actual and mental durations. It can be argued that timing processes in action and the mental simulation of action are interrelated and probably based on common timing mechanisms. However, the absolute error converted into a percentage shows that this correspondence is far from perfect. Mean percentage absolute error ranges from 21.0% to 23.7%. This finding may be due to differences in calculations in contrast to other studies. In the present study, absolute error is calculated for each mental trial before being averaged; unlike in the Decety, *et al.* study (1989), each condition is repeated 10 times, and the correlational data are based on averaged data for each condition. In addition, the experimental procedure differs because each condition is repeated only once by each subject.

The analysis of the two mental instructions of eyes open versus eyes closed during mental simulation gives no significant differences. This is interesting because a mental image with eyes open requires only an image of the movement, whereas a mental image with eyes closed requires an image of the movement and of spatial proportions. These additional requirements could be expected to lead to greater deviations. However, this is not the case in the present experiments. Two different hypotheses may explain this. First, it is possible that the two conditions do not differ in difficulty as far as mental imagery is concerned. This may be due to a strong link between the images of movement and spatial proportions. From the perspective of action theory, it would be difficult to imagine one's movement without its situational components (see Munzert & Hackfort, 1999). As a result, there may well be no difference in processing the mental image: both cases initiate processing of movement and spatial requirements. A second hypothesis is based on visual interference, which appears when imaging with eyes open. Perhaps actual vision interferes with imagination and leads to a decrement in visualization. Similar processes have been discussed by Kosslyn (1994). This is an experience people can describe, and most people report a preference for movement imagery with eyes closed if given the choice. It is not possible to decide whether one of these hypotheses explains the lack of differences on the basis of the present data. Nonetheless, it is worth continuing to search for differences in these imagery modalities to ascertain whether imagery is task-dependent or whether the lack of differences really is general.

To broaden the investigation of timing accuracy, we have calculated a separate analysis of speed. This also extends the results of Decety, *et al.*'s study (1989). Speeds can be calculated for the Active conditions with eyes open and eyes closed and for the Mental conditions with eyes open. In the latter case, this is based on mental time and the seen distance. Higher speeds in Exp. 1 compared with Exp. 2 can be attributed to eyes open and eyes closed conditions for active trials. Riding a pedalo with closed eyes induces a feeling of uncertainty that leads people to be more careful. Although based on anecdotal reports, this seems to offer a plausible explanation of differences between the two experiments. Higher speed for longer distances (significant interaction of Speed and Distance) reflects the experience of accelerating the pedalo. This can be observed in all Active and Mental conditions except for Active/eyes closed. A significant two-way interaction for Conditions and Distance is a result of an overestimation of speed on longer distances. When it is considered that distance is exact in Mental conditions with eyes open, this has to be a reflection of speeds being too high or mental durations being too short. Because correlations indicate that timing data are somewhat more stable than speed data, these effects are probably due to deviations in speed.

In summary, the correlational data and, to some extent, the errors seem to support Decety, *et al.*'s position (1989). There is a clear correspondence between actual and mental durations when riding a pedalo. This is still the case when refined methods are used. The present experiment uses more distances and conditions, and correlation coefficients are first calculated and then averaged (using Fisher's Z transformations) and not vice versa. Nonetheless, statistical analyses yielded correlation coefficients of .86 to .93 for absolute durations. However, it would be wrong to overgeneralize these results. They are valid for cyclical, closed skills like walking, drawing, and riding a pedalo but not for discrete (like golf putting) or open skills (like badminton).

A next step could be to ask from whence these differences come. It seems reasonable to suppose that they reflect differences in the contributions motor representations make to open and closed skills. Whereas they are a central aspect in closed skills, contextual conditions are more crucial in open skills. This makes it necessary to assume different timing mechanisms for the two types of skill: one is a part of motor processes (and is, therefore, relevant in closed skills); the other is a part of event perception and imagination (and, therefore, relevant for open skills). These rather speculative assumptions may explain the different mental timing effects for open and closed skills. Neurophysiological analyses support this view by differentiating brain activities related to motor images into those that are motor-specific and those that are relevant for visuospatial information (see Parsons & Fox, 1998; Parsons, Gabrieli, Phelps, & Gazzaniga, 1998). However, there is no

guarantee that they are responsible for the differences between open and closed skills. Further research is needed to analyze the variables affecting mental timing in open and closed skills in different ways.

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