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Effect of Gravity on Learning and Memory of Prism Adaptation

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***Abstract*— Our body motion is adjusted properly under 1G on the earth. Thus changes in gravitational environment have significant impact on our motor control. Further, it may affect on our ability in motor learning and memory. Although some astronauts informally reported difficulties in their body control under microgravity, no quantitative research on this issue has been conducted. Here we performed the prism adaptation of a hand-reaching task under different gravitational environments. We compared learning and forgetting curves, and memory retention rates of the prism adaptation performed in upright vs. supine position under 1G, and those under 1G vs. 2G in upright position. We demonstrate that quicker learning, less forgetting and greater memory retention rates are obtained in supine position and under 2G in comparison with their counter part.**

I. Introduction

MICRO gravity imposes various effects on human body such as malfunctioning of cardiovascular system, weakening of muscle strength, reducing calcium from bones, and inducing space motion sickness [1]. Further, under micro-gravity, physical movements of astronauts and cosmonauts are slow and somewhat awkward. Motor control systems of our body are continuously calibrated by interacting with gravity on the earth, thus require re-adjustments in the brain motor areas when gravitational environment is changed. This is not only due to the direct effects of gravity on the mass of the body, but to the effects on sensory systems such as vestibular and proprioceptive systems as well. Although some astronauts have made subjective reports informally, scientific evidence on motor learning and memory retention under different gravitational environments is missing. In the present study, we address this issue by evaluating learning and memory retention curves of prism adaptation in a hand-reaching task under different gravity conditions. We compare upright versus supine positions, and 1G versus 2G hyper-gravity conditions.

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II. Methods

A. Equipment

A tablet PC (ThinkPad X61, 12.1 inch, Lenovo) with a touch panel screen was used to display a visual target and to measure reaching locations. Subjects wore goggles with prisms (Press-On Optics, 30D, displacement angle approx. 16.7deg to the left, 3M) (Fig.1) and hold a touch pen to which the touch screen of the PC responds. They sat in front of the screen with the distance 45 cm apart from their eyes. In this configuration, the screen covers 30.5 and 23.1 degrees of visual angles horizontally and vertically, respectively. The 16.7 degrees prism displacement corresponds to approx. 13.5 cm on the screen. The visual target is displayed as a red filled circle with the diameter of 5mm on a white background. Trajectory of the touch pen on the screen was marked in blue as the location where the subject touched.

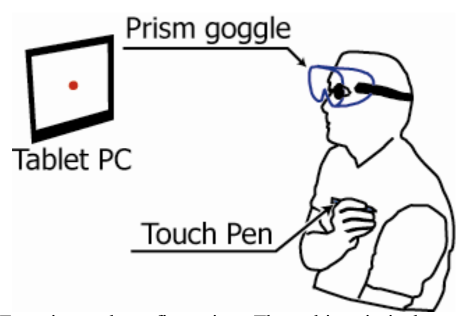


Fig. 1. Experimental configuration. The subject is in home position, wearing goggles with prisms, holding a touch pen in front of his chest, and sitting in front of a tablet PC positioned at 45 cm apart from his eyes.

B. Reaching tasks in learning and memory

The subject holds the touch pen comfortably with his dexterous hand in the “home position” as shown in Fig. 1.

One reaching task during the learning period consists of 4 steps as follows: 1) look at the visual target in the home position and memorize the location of the target. 2) close his eyes when hear a beep sound. 3) after 1 second, when hear the second beep sound, reach to the remembered target at his natural reaching speed, touch the screen with the pen, and return to the home position. 4) immediately open the eyes, confirm the touched location, and recognize displacement from the target, namely the error. The reason for reaching to the remembered target with his eyes closed is to avoid on-the-go correction of reaching behavior by using visual

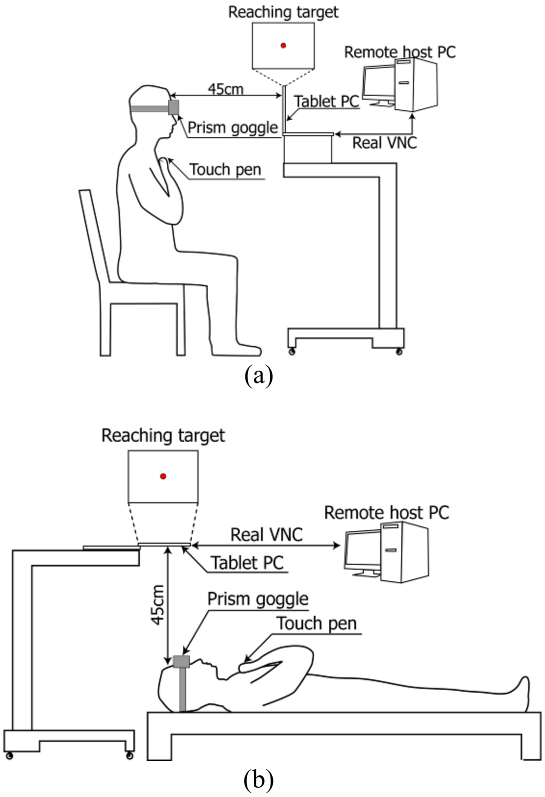


Fig. 2. Experimental configurations for upright (a) and supine (b) position experiments.

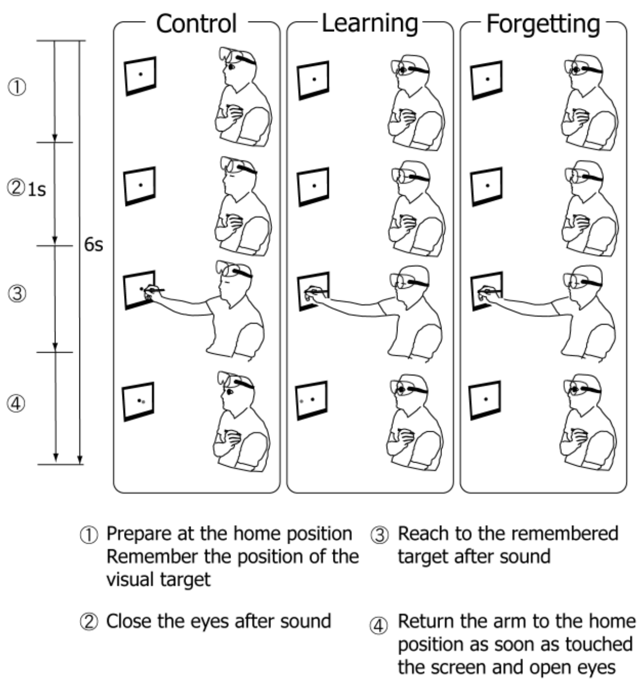


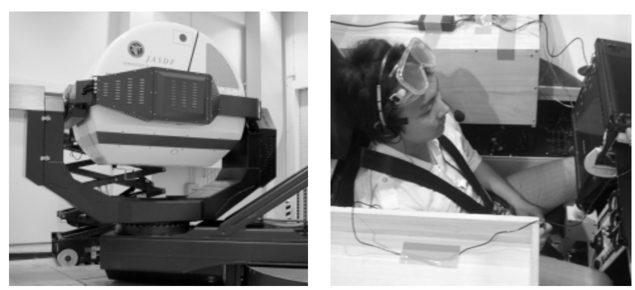
Fig. 3. Experimental procedure. The experiment consists of 3 blocks in each condition; control, learning, and forgetting.

information about the displacement of the pen from the target.

One reaching task during the memory retention period consists of the same procedures as the learning period, except in the step 4) in which the subject cannot confirm the error because the touched location is not marked visible. These 4 steps in 1 reaching task in both learning and memory periods take approx. 6 seconds in total. The subjects were told to reach where they see the visual target and not to consciously compensate for the displacement they perceive when putting on and off the goggles. They were also told to perform the reaching task at their natural speed.

C. *Upright vs. supine positions*

In order to evaluate how the difference in the relative angle between gravitational axis and the body axis affects on the learning and memory of prism adaptation of the reaching task, we employed 2 different postures under 1G condition, namely upright and supine as shown in Fig. 2 (a) and (b), respectively. The experiment was performed in a dark room to minimize differences in these 2 conditions other than their postures. In both upright and supine position conditions, the experiment consists of 3 blocks (Fig. 3). The 1st block is for acquiring control data in which the reaching task for learning is repeated 20 times without wearing the goggles. The 2nd and the 3rd blocks are the learning and memory blocks in which the reaching task for learning and memory are repeated 60 and 70 times, respectively. These 3 blocks were executed in series without taking any break between the blocks. After an hour or longer break on the same day, the experiment was performed in the other posture in the same subject.



(a) (b)

Fig.4. Spatial orientation training system (a), and a subject inside the system (b).

D. *1G vs. 2G conditions*

In order to evaluate how the magnitude of gravity affects on the learning and memory of prism adaptation of the reaching task, we compared data obtained under hyper-gravity (2G) with those under normal gravity (1G). The hyper-gravity environment was achieved by using the spatial orientation training apparatus at the Aeromedical Laboratory, Japan Air Self-Defense Force (JASDF) (Fig. 4a). The apparatus was tilted in roll and rotated at 3.05m off-axis to create 2.0G along the subject's body axis. A subject was seated in front of the touch screen that was also used for the experiments for upright versus supine postures (Fig. 4b). The position of the subject seat was adjusted so that the distance from subject's eyes to the screen becomes 45cm as in the experiments for different postures. All light sources in the apparatus were turned off to make the same dark condition as in the experiment for different postures. The experimental protocol is also the same, consisting of 3 blocks (control, learning, and forgetting). However, the number of trials in each block was set as 20, 60, and 70 for control, learning, and forgetting block, respectively. Experiment under 1G condition was executed always before 2G to avoid potential effect of hyper-gravity on 1G condition in case the order is reversed.

E. Data analysis

Each subject repeated the same experiments multiple times, thus data analyses were conducted on the mean learning and forgetting curves in each subject. The mean learning and forgetting curves were normalized by using the average value of initial 3 reaching displacements from the target. The normalized mean learning and forgetting curves were fitted by eq. (1) and (2), respectively.

$$L(n) = Ae^{-\frac{1}{\tau_L}(n_L - 1)} \qquad (1)$$

$$F(n) = (L_f - B)e^{-\frac{1}{\tau_F}(n_F - 1)} + B \qquad (2)$$

where A denotes the magnitude of the normalized initial error that was fixed to 100, τ_L: the time constant of learning curve, n_L: the number of trial in the learning block, L_f: the final value of the learning curve, τ_F: the time constant of the forgetting curve, n_F: the number of trial in the forgetting block, B : the asymptotic value of the forgetting curve, namely the magnitude of memory retention. Thus, (A-L_f) indicates the amount of learning. We also defined the memory retention rate MM as follows with the final value of forgetting curve F_f.

$$MM = \frac{A - F_f}{A - L_f} \qquad (3)$$

III. RESULTS

A. Upright vs. Supine positions

Total of 8 healthy male subjects (age 21-42, average 24.6 years old) participated in the experiment. Each subject underwent the same experiment 5 times or more each on a different day. Among the 8 subjects, one that did not show memory decay but further learning during the forgetting block was eliminated from later analyses.

Fig. 5 (a) and (b) illustrates example normalized learning and forgetting curves in upright and supine positions from a typical subject. Gray traces are the normalized learning and forgetting curves averaged over 12 samples in this subject. Black traces are results of curve fitting to the gray traces by eqs. (1) and (2) for the learning and forgetting curves, respectively. The abscissa shows the number of reaching trials divided into 3 blocks: control (1-30), learning (31-80), and forgetting (81-150). The ordinate indicates normalized horizontal displacements from the target with positive values for leftward displacements. It appears that in supine position fewer trials are required to minimize the leftward displacement while more trials are required to forget the learned memory. To quantitatively compare the speeds of learning and forgetting in upright and supine positions, Fig. 5 (c) and (d) illustrate the time constants of the learning and

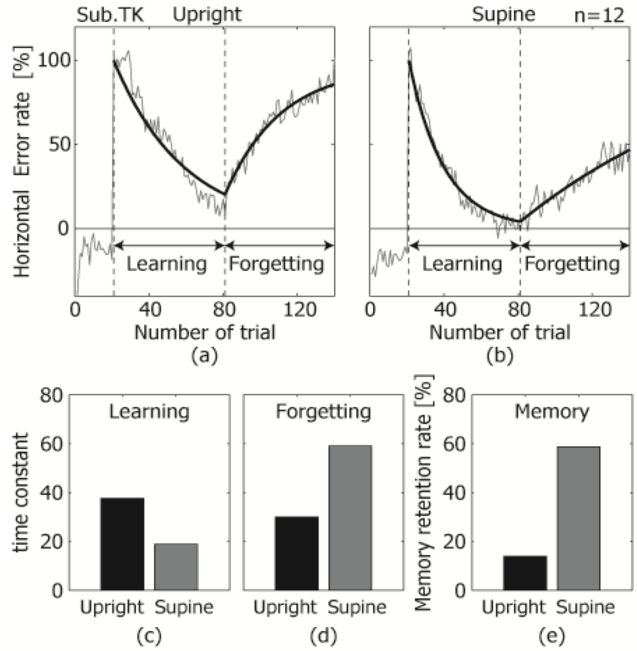


Fig.5. Example results of upright vs supine position experiments from a typical subject. (a): learning and forgetting characteristics in upright position, (b): learning and forgetting characteristics in supine position. In both panels, gray lines are averaged data over 12 samples, while black lines are results of curve fitting to the gray lines by equations (1) and (2). (c): comparison of time constants of learning curves τ_L, (d): comparison of time constants of forgetting curves τ_F, (e): comparison of memory retention rate MM.

TABLE 1
Summary of comparison between upright and supine experiments for all the subjects

Sub.	Learning time constant [num. of trial]		Forgetting time constant [num. of trial]		Memory retention rate [%]	
	Upright	Supine	Upright	Supine	Upright	Supine
TK	37.68	18.86	30.01	59.04	13.97	58.6
SM	66.39	46.70	12.87	35.50	61.36	86.41
TY	50.47	34.63	23.42	42.93	39.09	65.61
SY	39.59	24.75	27.06	68.84	6.86	12.65
HM	48.47	61.05	16.22	10.22	60.86	58.33
YH	44.98	13.11	5.05	4.56	45.20	66.26
YO	22.83	9.78	32.20	167.5	30.71	48.82
SK	106.7	29.45	5.495	15.992	16.85	57.84

forgetting curves estimated by the curve fitting. As seen qualitatively in the comparison of Fig. 5 (a) and (b), the time constant of learning in supine position is approx. 2 times smaller than that in upright position, while the time constant of forgetting in supine position is approx. 2 times greater than that in upright position in this subject. As the result, the memory retention rate calculated by eq. (3) for this subject is approx. 2 times greater in supine than upright position as shown in Fig. 5 (e). Table 1 summarizes time constants and memory retention rate for all the 8 subjects. In 7 out of the 8 subjects, learning is faster (smaller time constants) in supine position while only 1 subject showed faster learning in upright position. In 6 out of the 8 subjects, forgetting is slower (greater time constants) in supine position while 2 subjects showed slower forgetting in upright position. As for memory retention rate, 7 subjects showed greater values in supine position, while the opposite is true for only 1 subject.

B. *1G vs. 2G conditions*

Total of 6 healthy male subjects (age 21-42, average 24.7 years old) participated in the experiment. Among those, 4 subjects underwent the entire experimental protocol that consists of control, learning, and forgetting blocks. The rest omitted the forgetting block to perform another block of experiment (re-adaptation block) instead. Results of the re-adaptation experiment will be reported elsewhere.

Fig. 6 (a) and (b) illustrate example learning and forgetting curves under 1G and 2G condition from a typical subject in the same format as in Fig. 5 (a) and (b). It appears that under 2G condition, fewer trials are required to minimize the leftward reaching displacement during the learning period, while learned memory is forgotten more slowly than that under 1G condition during the forgetting period. To quantitatively compare the speed of learning and forgetting under 1G and 2G conditions, Fig. 6 (c) and (d) illustrate the time constants of the learning and forgetting curves estimated by the curve fitting as in Fig. 5 (c) and (d). As seen qualitatively in the comparison of Fig. 6 (a) and (b), the time constant of the learning curve under 2G condition is significantly smaller than that under 1G condition, indicating faster learning under 2G in this subject. In contrast, the time constant of the forgetting curve under 2G is much smaller than that under 1G condition, indicating slower forgetting under 2G. The memory retention rate calculated by eq. (3) for this subject is slightly greater under 1G than that under 2G. Table 2 summarizes time constants and memory retention rate for all the 6 subjects including those who didn't undergo the forgetting block. In all the 6 subjects, learning is faster under 2G condition. As for forgetting, 2 out of 4 subjects who underwent the forgetting block showed slower forgetting under 2G condition while only 1 subject (Sub. TK) showed faster forgetting under 1G. One of the 4 subjects (Sub. HM) yielded significantly different forgetting characteristics that cannot be approximated by eq. (2), thus the forgetting time constant was not evaluated in this subject (indicated as NG fitting in Table 2). No clear common tendency was found in the memory retention rate among the subjects.

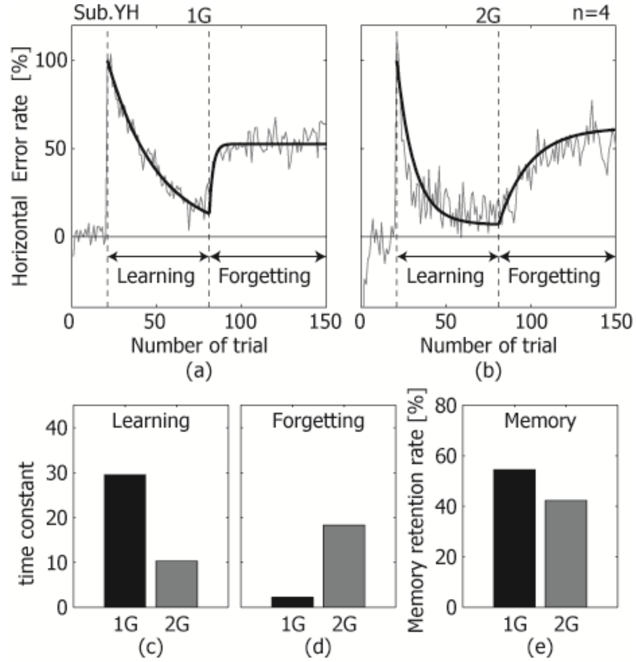


Fig. 6. Example results of 1G vs. 2G experiments. Formats are the same as in Fig. 5.

TABLE 2
Summary of comparison between 1G and 2G experiments for all the subjects

Sub.	Learning time constant [num. of trial]		Forgetting time constant [num. of trial]		Memory retention rate [%]	
	1G	2G	1G	2G	1G	2G
YH	29.48	10.32	2.21	18.27	54.48	42.26
SY	30.84	22.92	20.53	29.85	-5.61	-9.48
TK	30.66	9.14	26.96	12.79	25.93	39.07
HM	46.49	27.61	NG fitting	NG fitting	100.3	93.57
YO	23.56	14.13	-	-	-	-
YT	18.21	9.18	-	-	-	-

IV. Discussion and Conclusion

In both upright vs. supine and 1G vs. 2G experiments, learning in prism adaptation of hand reaching was faster and forgetting was slower in most of our subjects in unusual conditions, namely supine and 2G. To the best of our knowledge, this is the first evidence that demonstrated the effect of gravitational environment on motor learning and memory. The cerebellum is considered to play a crucial role in motor learning and memory. Recent imaging studies showed that it is also the case in the prism adaptation of hand reaching [5][6]. Cerebellar regions activated during prism adaptation of hand reaching are lobules IV and V [6] that receive vestibular mossy fiber input [7]. Other than these cerebellar regions, intraparaietal sulcus and inferior paraietal lobule are activated during the prism adaptation task [5]. These cerebral cortical areas receive projections from cerebellar crus IIp and paramedian lobule [8] that also receive vestibular input [9][10]. Thus it could be predicted that changes in the direction and magnitude of the gravitational vector may affect on the learning and memory in the prism adaptation of hand reaching task, although it was not evident whether supine position or 2G causes faster learning and slower forgetting.

Under 2G, not only vestibular input but also the weight of the arm itself changes. We tested the effect of extra weight on the arm in one subject (sub. TK in Table 2) by wrapping heavy flexible material around his arm to make it twice as heavy under 1G condition. Although he showed significantly different performance in 1G and 2G conditions, the extra weight around his arm under 1G did not cause any significant difference in learning and memory from those without the extra weight under 1G (data not shown).

We are not used to reaching in supine position or under 2G environment in our daily life nor in the process of evolution. This unusual environment per se, not necessarily specific to unusual gravitational environment, may cause faster learning and slower forgetting in motor learning and memory. So far, we haven't found any condition that results in the opposite effects, namely slower learning or/and faster forgetting than those in upright position under 1G. The same type of experiment under micro-gravity environment may test this possibility.

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