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Self-organized criticality and learning a new coordination task

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A B S T R A C T

The purpose of this study was to investigate the hypothesis that a self-organized criticality (SOC) practice condition would have a higher improvement rate in performance outcome than a typical progressive difficulty of practice regimen. The roller ball task was used where participants undergo a phase transition from failure to successful performance after sufficient practice. The findings from two experiments showed that the SOC condition had the fastest rate of improvement and the highest performance success level. The success probability in the SOC practice regime was close to the theoretically predicted value of 50%. It appears that the SOC practice condition – by scaling task difficulty to skill level in a self-controlled adaptive strategy – facilitates the learning of new movement coordination pattern by keeping the participant close to the parameter region of the transition of the movement dynamics.

1. Introduction

In a number of motor learning situations, such as in music and sport, the practice and instructional strategy plan is often provided by an instructor or teacher (Bund, 2005; Singer, 1975). However, there are also practice situations of self-controlled learning in which the learner is able to take control over the structure of certain aspects of the practice conditions and can explore and apply different learning strategies (McCombs, 1989). The self-controlled learning regimen holds some similar properties to that of self-discovery learning in which the participant controls all aspects of the practice regimen (Vereijken & Whiting, 1990).

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It has been proposed that the self-controlled learning strategy helps to maintain a high level of self-monitoring and attention to relevant information in movement feedback and correction (Behncke, 2005). In this view, the most important feature of the self-controlled learning strategy is to be able to detect the discrepancy between the present behavior and the task goal behavior based on the local objectives laid out under the overall task objectives. The learner has to be aware of their abilities and choose relevant objectives that have personal meaning to real life experience so that they are able to arrange appropriate successes and failures to meet the expected outcome and objectives (Kornell & Bjork, 2007; McCombs, 1989).

Wulf and colleagues have shown that providing the opportunity for some form of self-control of the practice session improves motor learning (Chiviacowsky & Wulf, 2002, 2005; Wulf & Toole, 1999; Wulf, Clauss, Shea, & Whitacre, 2001). With the ability to control the practice conditions, learners are more encouraged to explore a fuller range of strategies in practice and are more strongly motivated to perform well. Indeed, Janelle, Barba, Frehlich, Tannant, and Cauraugh (1997) found that when learners decide whether to have feedback or not after practice, the frequency of requested feedback decreases with practice and there was better retention of performance. One possible reason for self-controlled practice enhancing learning is that the reduction of the feedback frequency may help the learner to be more independent of feedback information when performing the task.

The concept of self-controlled practice regimens in motor learning is related to but *distinct* from the concept of self-organized criticality. The idea of self-controlled practice regimen refers to the strategy of the learner having control over the practice conditions (Vereijken & Whiting, 1990), whereas self-organized criticality refers to a particular theoretical account of changes in the qualitative dynamics of a wide range of phenomena (Bak, 1997). Many natural systems exhibit the phenomenon of self-organized criticality where the system spontaneously develops into a critical state (Bak, 1997) and minor perturbations can lead to a qualitative change of behavior (phase transition/bifurcation/catastrophe – e.g., Guastello, 1984; Haken, Kelso, & Bunz, 1985; van der Maas & Molenaar, 1992). In the classic example of sand pile behavior (Bak, 1997), grains are randomly dropped onto a surface. As the pile grows avalanches occur with frequency and size that increases with its control parameter, the slope of the pile. There exists a critical slope of the sand pile for which any additional grain of sand can trigger avalanches of any admissible size. This critical state is qualitatively different from sub-critical states, where an additional grain of sand will trigger at most small avalanches, as well as from super-critical states, where the overwhelming probability is that an additional grain of sand will trigger a maximum avalanche that will reduce the slope of the sand pile back to a sub-critical value. This condition of criticality is self organized in the sense that it is attractive in the space of the control parameter, namely slope. To achieve criticality it is not necessary to fine-tune the control parameter but to merely add grains of sand.

In motor learning, a critical condition can be interpreted as the point where a learner experiences the transition from failure to success in mastering tasks like bicycle riding or juggling, which have essentially an all or none property to the performance. We have identified practice time as the quantity that accumulates during learning in the same way that grains of sand are added to the sand pile (Newell, Liu, & Mayer-Kress, 2009). The control parameter that is influenced by practice time is skill level. It is the relevant control parameter (for a given task difficulty) that will eventually lead to a phase transition when a critical skill level is reached (Liu, Mayer-Kress, & Newell, 2006, 2010).

When the learner has had little practice time on a task that requires a transition for success, the skill level of the learner is low corresponding to a small slope of the sand pile in its sub-critical state. An additional trial will often lead to no or only small improvements in performance corresponding to small avalanches on the sand pile. Accumulating practice time increases the skill level and eventually leads to a state of criticality where the next trial now has a probability of a performance value that can range all the way from poor (failure) to high (success). This wide range of performance values only becomes possible once the state of criticality has been achieved. This situation is often referred to as that the learner has not yet stabilized the performance of the task. Using the sand pile analogy for the motor learning condition, the skill level is like the slope of the sand pile where a flat slope induces little avalanche, and dropping more sand on the pile increases the slope of the sand pile. In the motor learning case, low skill level has small success rate and increasing practice time increases the skill level.

Practice time, however, cannot be moved back and forth freely as in control parameters such as movement frequency in the HKB model (Haken et al., 1985). Therefore, it is difficult to observe the behavioral phase transition more than once for the same learner as has been shown to be the case in the sand pile example. However, the skill level of a learner is related to the level of task difficulty. Using skill level of the learner and the difficulty level of the task as a pair, we proposed a "dual" control parameter based on the mathematical concept of duality of vector spaces (Newell, Liu et al., 2009). Practice level and task difficulty were manipulated and modeled as two control parameters that theoretically were hypothesized to change the threshold for the transition between task success and failure. Thus, in the adaptive learning strategy of continuously increasing the task difficulty, we can reach a point where the skilled participant can no longer successfully perform the task and will experience a transition back to the low score "failure" state.

The roller ball used in the experiments of this paper was a spherical top covered with a layer of hard spherical outer shell. There is a 3.5-cm-diameter circular opening on the outer shell which makes available the direct contact to the inner top. The roller ball player grasps the 7-cm-diameter roller ball in the hand, and tries to keep the spherical top spinning at/above the required speed using the hand/wrist movement (Fig. 1). To start the roller ball task, the player has to spin the inner top of the ball with an external force. This can be done either by using a string inserted into a hole at the equator of the inner top and wrap around the equator several circles then pull out the string, or with a more advanced player, directly rubbing the inner top at the opening of the outer shell.

The initial speed of the inner top of the ball (the ball speed) was used to represent the task difficulty. The learner starts the task with a high initial ball speed corresponding to low difficulty. Continuing to practice the task increases the skill level which is equivalent to reducing the relative difficulty of the task. To successfully perform the rollerball task, the learner needs to learn a particular spatial phase relation between the motion of the ball and that of the outer shell whose motion is controlled by the hand (Liu et al., 2006). This transition has been modeled as a saddle-node bifurcation corresponding to a first order phase transition (Liu et al., 2010). Once the learner has progressed through this transition and learned the task the initial ball speed can be lowered and, therefore, the task difficulty is increased again. This experimental strategy is a type of adaptive learning where the task conditions are changed to map the difficulty to the changing skill level of the learner (Proctor & Dutta, 1994). It is also consistent with the more general notion that difficulty of the learning conditions is an important variable that influences the learning and retention of motor skills (Bjork & Linn, 2006; Schmidt & Bjork, 1992).

Fig. 1. The top view of a roller ball that was used in the experiments. The opening on the outer shell reveals the inner top which spins when applying torque from the outer shell. The equator of the inner top was painted half white and half black in order for the optic fiber to detect the different reflective light.

In the context of the sand pile model the observation of "being able to perform the task successfully" would correspond to a situation where an additional grain of sand would have a very high probability of triggering a maximum size avalanche. Whereas conservation of mass will automatically take the sand pile into a sub-critical state, in motor learning a second process is needed to achieve that same goal. Factors such as boredom, loss of challenge etc. will motivate the learner to increase the task difficulty, which is permissible in the SOC protocol of this report. This increase in task difficulty is continued until a difficulty level is reached that takes the system back to a sub-critical state with low probability of success (high performance outcomes corresponding to large avalanches). The dual control parameters of practice time and task difficulty change the threshold of the transition in the learning dynamic. Increasing the control parameter by continuing practice leads to the transition point and reaching the supercritical region and further increasing the control parameter by increasing the task difficulty takes the performance state back to the subcritical region.

One aspect in which the motor learning situation is different from the simple sand pile lies in the fact that the difficulty can be reduced, usually in a situation far from criticality, where the learner would experience many sequences of low scores of failure. The task difficulty can be reduced arbitrarily, in the roller ball situation reported here, by increasing the initial ball speed. In spite of these differences in detail, the main characteristic features of SOC can be found in our motor learning example. There exists an attractive parameter combination (forming a manifold in parameter space, see below) for which the system exhibits criticality and a distribution of performance values at criticality that has a wide distribution (Bak, 1997). This latter point has not been quantitatively confirmed yet due to the lack of sufficient data on phase transitions in motor learning.

Liu et al. (2006) found that when the learner starts at a low initial speed, it may take a considerable number of trials before he/she experiences a successful performance. During the practice period of continuous failure, the learner may lose motivation and never realize a successful performance or forget what the successful performance feels like. Continuing failure in the task will also result in a low success rate in that low success rate through more difficulty in practice leads to less effective learning (Maxwell, Masters, Kerr, & Weedon, 2001). Practicing the task for a skill/difficulty parameter combination for which the success rate is close to 100% is also not attractive, because a task that is too easy will quickly become boring for a learner as they perform in a limited segment of the control space.

In this study we investigated whether for a self-organized practice condition, where the learner has control over the selected task difficulty during practice, extrapolation from the dynamics of self-organized criticality would predict that an attractive critical manifold exists in the skill/difficulty space that is characterized by a 50% success. Because the transition from failure to the success plays a key role in learning the task, we hypothesized that learners would try to keep the learning dynamics at the transition so that they would stay at the "edge" of achieving a higher performance level. The 0 % success indicates a total failure and the 100% success represents a complete success. The 50% success rate lies in the middle of the 2 attractor states and therefore is used as the first approximation of performance statistics when the transitions occur. That means a learner would increase or decrease the difficulty level of the task until it reaches the critical value where the chance for success is close to 50%. It should be noted that the 50% success rate is also consistent with a motivational account of difficulty proposed by Atkinson (1957) where too low a success rate will impose too big a challenge but too high a success rate will bore the learners. The 50% success rate practice condition maximizes the uncertainty for the learner and this is linked to high motivation and performance level. Thus, the SOC learning group was contrasted with a progressively increasing difficulty (PID) condition, a learning strategy that is more common in motor learning (Holding, 1965; Proctor & Dutta, 1994).

2. Experiment 1

Experiment 1 examined 2 groups of learners where the task difficulty during practice was either self-organized (SOC) or externally determined in a progressively increasing difficulty (PID) practice regime. The step of increasing or decreasing task difficulty was set to be the same for both groups, and the 50% success rate was predicted to emerge from the self-organized practice regime given that its value maximizes uncertainty (Atkinson, 1957).

2.1. Methods

2.1.1. Participants

Twenty young adult volunteers participated in the study and were randomly assigned to one of the two experimental practice groups. The experimental procedures were approved by the Penn State University IRB committee, and all participants signed a consent form before engaging in the experimental tests.

2.1.2. Apparatus

A roller ball (Dyna-Flex International, Gyro Pro Plus) is a spinning top whose axis of rotation can move freely in a circular groove inside of a spherical shell that is held and moved in one hand (see Liu et al., 2006 for a detailed description of the device). Half of the region around the equator of the roller ball was painted black and the other half was painted white. Two strings of optical fiber were inserted into a hole on the shell where the two rotational axes intersect. The fiber optics were connected to an active light sensor (Riko) that emitted and received the reflected light. The pulse rate of the reflected light measures the rotation speed of the ball and was then sent to a PC computer via a 16 bits A/D board (National Instrument, 6034E) at a sampling rate of 200 Hz.

2.1.3. Task

The task was to use the dominant hand to manipulate the roller ball so that at the end of the 10 s trial the rotational speed of the roller ball would be at or above the initial ball speed of the trial. The 10 s trial duration was considered as appropriate based on learning data from a previous experiment (Liu et al., 2010). The level of the first initial ball speed was determined individually from the pre-test section.

2.1.4. Procedures

The two groups were PID (progressively increasing difficulty) and SOC (self-organized criticality). Each participant started the experiment with the pre-test followed immediately by the first practice session on day 1, followed by an additional 4 days of practice sessions after that. The last day of practice was followed immediately with the post-test session.

2.1.4.1. Pre-test session. The initial speed of the roller ball for pre-test was 40 rps. The 40 rps was based on a previous study (Liu et al., 2010) of the roller ball task that had a difficulty level so that most of the novice participants were able to perform the task successfully. Here, the participant was asked to roll the ball so that at the end of the 10 s trial the ball speed would be at or above the initial speed. An important feature of the roller ball task is that the spinning ball provides haptic feedback whereby the performer knows whether the task was successful or not. In addition, a computer generated audio feedback indicating a success or failure performance at the end of the 10 s was provided to confirm the result of the trial performance. If the participant succeeded, the experimenter decreased the initial ball speed by 10% and the participant was to perform the 10 s trial again. This procedure of reducing the initial ball speed continued until the participant failed to maintain or increase the spinning speed at the end of the 10 s trial. The lowest initial ball speed observed was 12.55 rps. If the participant failed the 10 s task at 40 rps the experimenter increased the initial speed by 5 rps steps (i.e., 45, 50, 55 and 60 rps) until the participant successfully performed the task. The highest initial ball speed used was 60 rps. These initial ball speeds were used at the beginning of the 30-trial pre-test.

Using the individually determined lowest successful initial ball speed as the starting speed, the participant was tested with a more precisely assessed level of ball speed for 30 trials to determine the starting performance level. During the 30-trial test, if the participant succeeded 8 times in 10 consecutive trials, the initial ball speed was lowered by 10%. If the participant failed 3 times in a row, the ball speed was increased by 5%. This procedure was implemented to provide a stable estimate of the skill level of the participant. Table 1 shows the start and the end initial ball speed for the 30-trial test.

2.1.4.2. Practice session. There were 50 practice trials on each day for every participant. All participants were instructed that the task goal was to try their best to keep the ball rolling at the lowest initial ball

Table 1
The initial ball speed (rps) for the start and the end of the 30-trial pre-test.

	Individual participant									
	1	2	3	4	5	6	7	8	9	10
SOC start	60.00	32.40	15.50	40.00	12.55	26.24	17.22	36.00	29.16	29.16
SOC end	60.00	29.16	14.73	40.00	13.78	24.93	18.66	29.16	26.24	21.26
PID start	36.45	12.55	13.95	60.00	60.00	17.22	60.00	29.13	19.13	23.91
PID end	32.81	13.25	13.25	60.00	60.00	15.50	60.00	23.62	21.32	23.91

speed that they could achieve. For the PID group, the initial ball speed was determined by the pre-test lowest speed. If participants in this group succeeded 8 times in 10 consecutive trials the experimenter lowered 10% of the initial ball speed. If the 8-in-10 criterion was not met, the participant continued to practice at the same initial speed. PID practice strategy has been shown to be an effective learning procedure in an earlier rollerball learning experiment where multiple transitions were observed over 10 days of 500 practice trials (Liu et al., 2010). For the SOC group, the participants chose any speed as the initial ball speed of the first trial. If the trial was successful, the participant could choose to stay at the same speed or lower the initial speed by 10%; if the trial was not successful, the participant decided whether to stay at the same speed or increase the speed by 10%.

2.1.4.3. Post-test session. The initial speed of the roller ball for the first trial of the post-test was the lowest speed of the pre-test. The same 30-trial procedure used in the pre-test session was applied in the post-test session.

2.1.5. Data analyses

The average angular acceleration for each trial was used to evaluate the task performance. The average angular acceleration was calculated as the difference of the initial and the end spinning speed of the roller ball divided by the trial duration (10 s). If the end speed was the same as or greater than the initial speed, the average angular acceleration would be equal to or greater than 0 rps/s, then the trial would be considered successful. A negative average angular acceleration would indicate a failure trial. The piecewise linear regression was used to examine the rate of performance change before and during transition (Liu et al., 2006).

The daily success rate was calculated by the number of successful trials divided by the total number of trials performed in a day (50). The mean daily success rate of each participant was used for statistical analysis. In order to calculate the improvement rate, the difference between the lowest initial speed which had met the 8-in-10 criterion in the post-test and in the pre-test session was calculated. The improvement rate was derived by taking the difference divided by the lowest 8-in-10 initial speed from the pre-test.

The daily success rate between the 2 practice groups was compared by an independent sample t test, and the success rate of each group was also tested against the predicted 50% success rate by way of the one sample t-test. The improvement rate of the 2 practice groups was compared with the independent sample t test.

2.2. Results

2.2.1. Performance curves and transitions

The two groups of participants, PID and SOC, practiced 250 trials of the roller ball task over 5 days. Fig. 2 shows some example performance curves of the participants for each group. Panels A and B of Fig. 2 show the typical performance curves of the SOC group where the trial performances fluctuated around 0 throughout the 5 days practice because the participants could choose to increase or decrease the task difficulty (initial ball spinning speed) based on the current trial performance. Although the SOC procedure did not afford a formal examination of the transition within a difficulty level, most of the participants did show a fluctuating performance outcome indicative of unstable task dynamics.

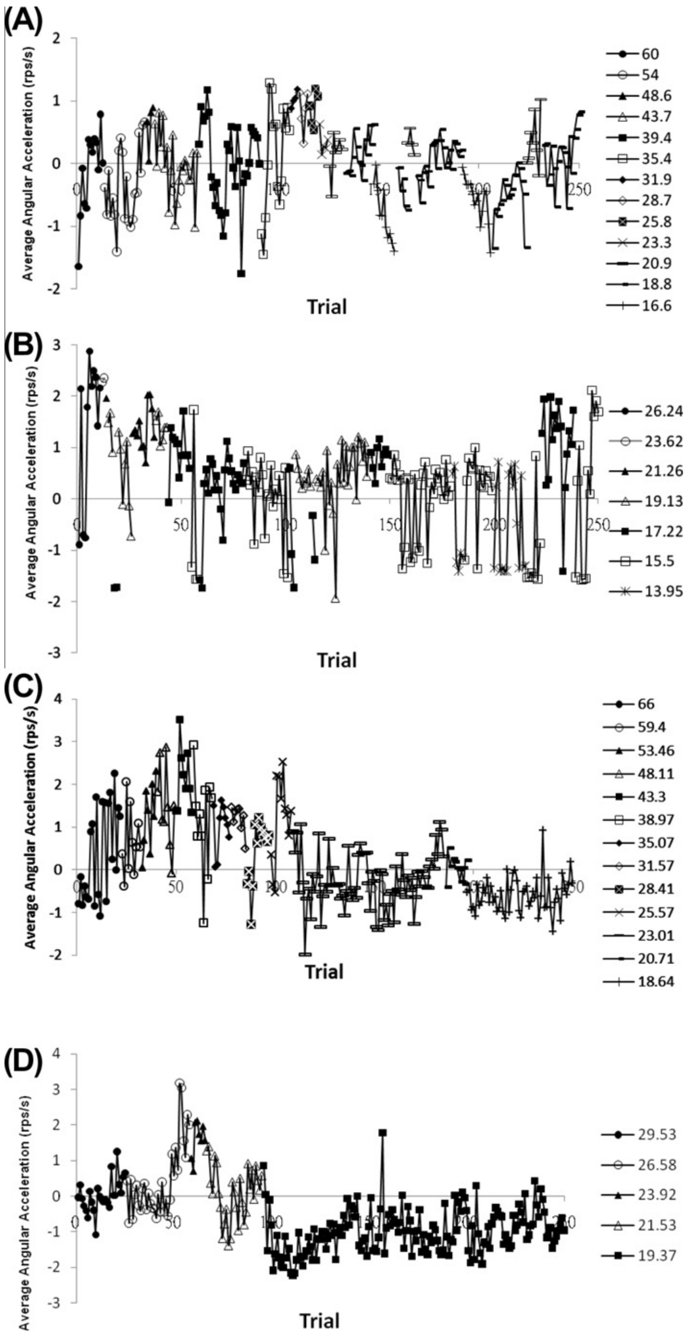

Fig. 2. Example individual performance curves over 250 practice trials. The goal of the task was to roll the ball at or above the initial ball speed at the end of the 10 s trial and, therefore, we take the difference of the ball speed between the end and the beginning of the trial then divided it by the 10 s trial duration to get the average angular acceleration as the performance measure. Panels A and B are the performance curves of 2 participants from the SOC group. Panels C and D are the performance curves of 2 participants from the PID group. Each symbol in a graph represents one difficulty level indicated by the initial ball spinning speed in unit of revolution per second (rps).

These unstable dynamics suggested that under the SOC procedure, the participants tended to keep the task dynamics at the transition level all the time by changing the skill level (adding practice trial) and the task difficulty (changing the initial ball speed).

Panels C and D of Fig. 2 which demonstrated the typical performance curves of the PID group, however, did not show such a constant fluctuation around 0 throughout the 250 practice trials but rather longer strings of negative average angular acceleration (the failure trial performance) toward the later practice trials. Because the PID group could not change the task difficulty of the practice trials until the 8-in-10 criterion was met, we were able to examine the transition of the task performance within the same task difficulty.

Based on the multiple time scales landscape model of motor learning (Newell, Mayer-Kress, Hong, & Liu, 2009), we approximated the rate of performance change with a piecewise linear model (Liu, Mayer-Kress, & Newell, 1999; Liu et al., 2006). For each difficulty level, the approximate linear rate of performance change of the last 20 trials (10 trials before the final success plus the last 10 trials) and the earlier trials was compared in order to examine the increase of rates during the transitions. We only used the trial segments where there were more than 40 trials for each task difficulty for the comparisons. Two participants did not have data from any difficulty level that met the 40-trial criterion. Table 2 shows the rate of performance changes within the same task difficulty from the PID group. The result of the paired *t*-test showed a significant increase of the approximate linear slopes from the earlier trials to the last 20 trials within each task difficulty, $t(15) = -4.83$, $p < .001$. This result was consistent with the findings in the earlier rollerball study (Liu et al., 2006) where the rate of performance change increased significantly during transition. Note that there were 6 participants who demonstrated multiple transition phenomena over the 250 trials performance.

2.2.2. The success rates and the improvement rates of task performance

One participant from the SOC group did not change the initial ball speed for the entire 5 practice days. As a result, she did not improve performance in the task which was indicated by no difference of the lowest initial speed between the post and pre tests. Although this outcome is one of the possible consequences of implementing a self-controlled practice regime, the behavior demonstrated by this participant was clearly contrary to the assumption that all the participants were trying their best to improve performance. Therefore, the data from this participant were excluded from analyses.

The independent sample *t*-test on the daily success rate showed a significant difference between the 2 practice groups, $t(17) = 1.9$, $p = .04$, indicating a higher success rate for the SOC group (see Table 3). Further examination of the SOC group performance revealed that their success rate was not different from 50%, $t(8) = .01$, $p = .99$. The success rate of the PID group, however, was significantly different from 0.5, $t(9) = -.287$, $p = .02$. The analysis of the coefficient of variation of the daily success rate also showed a significantly more stable rate for the SOC group compared to the PID group, $t(17) = 2.5$, $p < .05$. This was due to a consistent fluctuating performance therefore a close-to-50% daily

Table 2
The rate of performance change (slope) of different segments of the same task difficulty for the PID group.

	Participants							
	1	2	3	4	5	6	7	8
1st level (rps)	20.70	60	60	17.27	13.95	11.32	23.62	9.67
Earlier slope	0.0169	0.033	0.0081	−0.0051	−0.0014	0.0143	−0.017	0.0182
Last 20 slope	0.1808	0.0435	0.0057	0.1816	0.1153	0.0894	0.1026	0.0729
2nd level (rps)		18.83	20.93		11.30	10.19	21.26	8.70
Earlier slope		0.0809	0.0164		0.0294	0.0098	−0.0031	0.0003
Last 20 slope		0.0814	0.0529		0.053	0.068	0.0614	0.0368
3rd level (rps)							19	
Earlier slope							−0.0179	
Last 20 slope							0.05	
4th level (rps)							17.2	
Earlier slope							0.0189	
Last 20 slope							0.0713	

Table 3
Individual and mean daily success rate for the SOC and PID groups.

Participant	Success rate (average, SD, CV)					
	SOC			PID		
1	.512	.138	.270	.384	.187	.487
2	.492	.072	.147	.256	.165	.645
3	.296	.132	.447	.400	.188	.469
4	.448	.115	.257	.472	.277	.588
5	.364	.216	.593	.564	.251	.445
6	.564	.113	.200	.344	.122	.355
7	.772	.098	.126	.588	.254	.432
8	.564	.066	.117	.224	.059	.261
9	.492	.102	.203	.272	.183	.673
10	–	–	–	.372	.053	.143
Mean	.500	.117	.263	.388	.174	.450

success rate in the SOC group, whereas for the PID group the daily success rate tended to change from an earlier high success rate to the later low success rate (see Fig. 2).

For the improvement rate, because the difficulty was not shown to increase linearly over decreasing initial ball speed, we selected and paired 14 participants from the 2 groups who had matching performances at the start level, that is, similar lowest initial speed observed in the pre-test. The result of the paired *t*-test showed that the SOC group had a significantly higher improvement rate (26.57% ± 15.17%) than the PID group (16.53% ± 14.66%), $t(6) = 2.29$, $p = .03$.

3. Experiment 2

In Experiment 1 the success rate in practice for the SOC group was observed to be close to 50%, whereas the success rate from the progressively increasing difficulty group was significantly lower on average (.388) than 50%. It is possible that the increment of the difficulty in the PID regime which had an immediate effect on the daily success rate would also have an overall effect on the improvement rate for learning the roller ball task. In Experiment 2 the 5% and 20% conditions were implemented to the progressively increasing difficulty (PID) group and the condition for the SOC group remained the same in order to further examine the effect of the success rate on learning. In addition, an extended 2-week retention test was also administered to examine the persistence of the learning effect.

3.1. Methods

3.1.1. Participants

There were 21 healthy young adult volunteers participating in this study. The experimental procedure followed the National Taiwan Normal University research guidelines, and all participants signed a consent form before engaging in the experimental tests. The participants were randomly assigned to one of 3 experimental groups with a matching triplet based on the performance level of the pre-test results.

3.1.2. Apparatus

The equipment was the same as that used in Experiment 1.

3.1.3. Task

The task was the same as in Experiment 1.

3.1.4. Procedures

Before the pre-test, every participant was tested on the task at the initial speed of 40 rps. If the participant could perform the task, the initial speed was lowered by 10% and the participant performed the task again with this initial speed. This procedure was repeated if the participant was able to continue to perform the task. The lowest speed at which the participant could perform the task was used as the starting speed in the pre-test. In order to have a similar starting performance level, the participants were grouped into sets of 3 based on the pre-test result and within the set, each participant was randomly assigned to one of the 3 experimental groups.

3.1.4.1. Pre-test. The pre-test procedure was the same as in Experiment 1.

3.1.4.2. Practice. Based on the results of the pre-test, the participants were randomly assigned to 1 of the 3 practice conditions according to the value of their lowest successful initial speeds. The first practice group followed a "Progressively Increasing Difficulty by 5%" strategy (PID5) where participants started with their individually determined initial speed until they successfully learned that speed (met the 8-in-10 criterion), and then the initial speed was lowered by 5% of the successfully learned speed. The 2nd practice group followed a "Progressively Increasing Difficulty by 20%" strategy (PID20). The participants who were assigned to this group followed the same practice requirement as the PID5 group except they lowered the initial speed by 20% of the successfully learned speed. The 3rd practice group practiced the task with the SOC strategy where the participants decided if they maintained the same initial speed or lowered the initial speed by 10% for the next trial when they could perform the task, and chose to stay at the same initial speed or increase the initial speed by 10% for the next trial when they failed to perform the task. All of the participants followed their specific practice strategy for 5 consecutive days, 50 trials a day.

3.1.4.3. Post-test. There were 2 sessions for the post-test, an immediate post-test that was carried out at the end of the last day of practice, and a post-test that was conducted 2 weeks after the last practice day. Every participant was tested in 30 trials for each post-test session, and the general procedure for the post-test was the same as in Experiment 1.

3.1.5. Data analyses

The daily success rate and the improvement rate from the 3 groups were analyzed as in Experiment 1. In addition, the immediate retention and 2 week retention performance from the 3 groups were also analyzed using a 2 way mixed ANOVA.

3.2. Results

The one way ANOVA on the overall success rate showed a significant group effect, $F(2, 18) = 7.28$, $p < .01$. The post hoc Bonferroni paired comparison indicated a significant difference between the SOC and PID20 ($p < .01$), and between PID5 and PID 20, ($p < .05$). No significant difference between SOC and

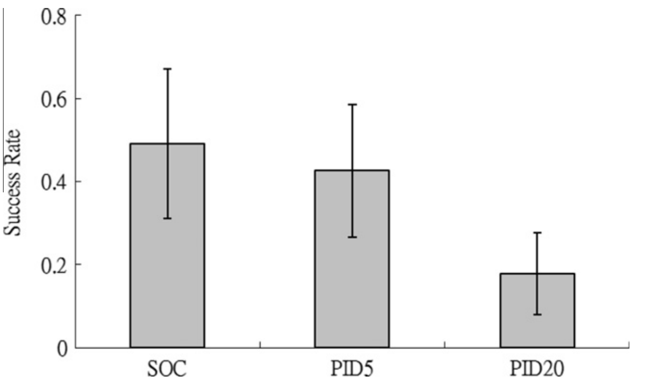

Fig. 3. Mean success rate (with between-participant *SD*) as a function of practice condition (SOC, PID5, PID20).

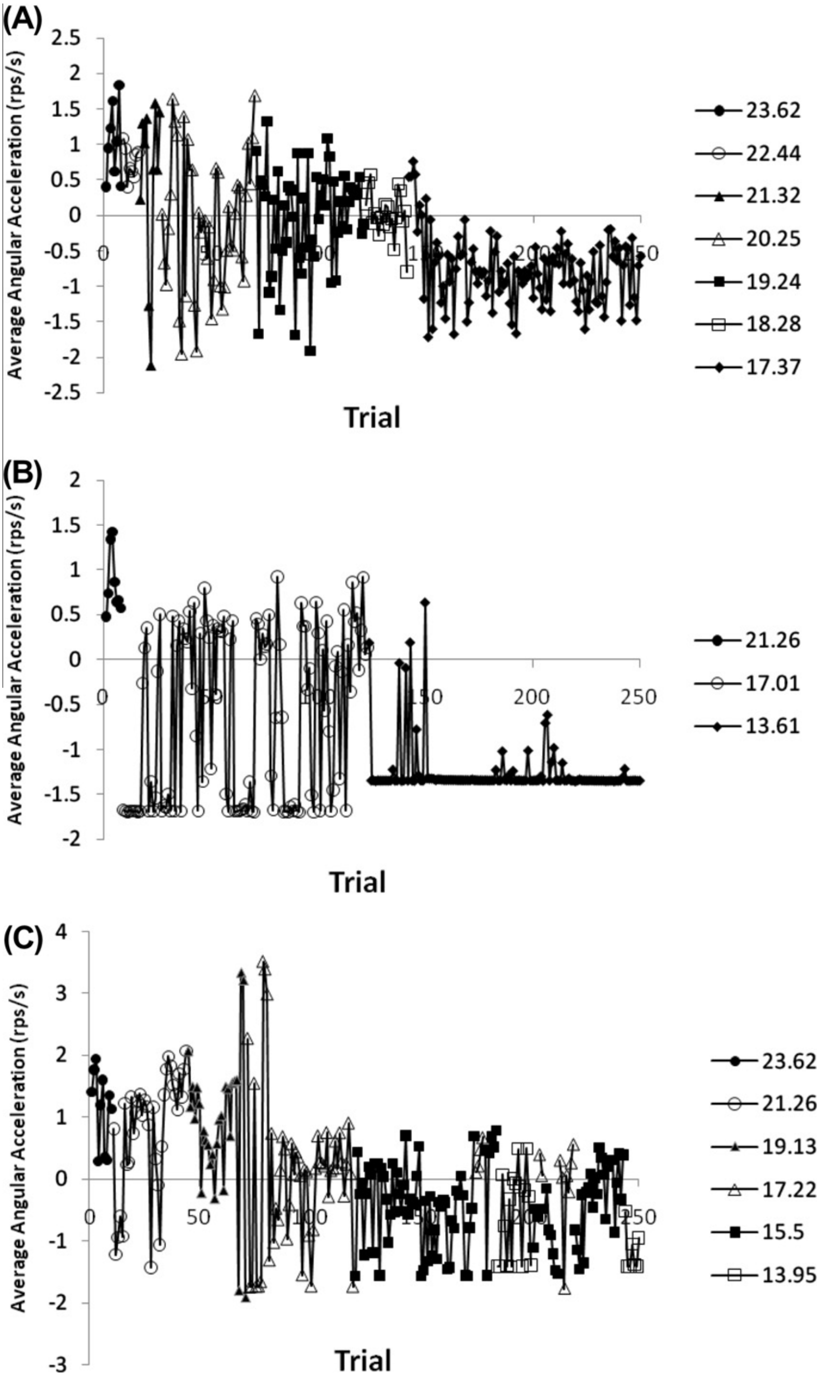

Fig. 4. Example individual performance curves over 250 practice trials. Panel A shows the performance curve from a participant in the PID5 group, panel B shows the performance curve of a participant in the PID 20 group, and panel C shows the performance curve of a participant from the SOC group. Each symbol in a graph represents one difficulty level which was indicated by the initial ball spinning speed in unit of revolution per second (rps).

PID5 was found, $p > .05$ (see Fig. 3). Further examination of the success rate of each practice group using the one sample t-test revealed that the success rates of the SOC (0.49) and PID5 (0.43) groups were not different from 50% ($p > .1$) whereas the PID20 (0.18) group was significantly smaller than 50% ($p < .001$).

Although the SOC and PID5 groups both showed a success rate that was not different from 50%, the small step of 5% increment rate in difficulty level might have resulted in a higher success rate in the earlier trials but a lower success rate in the later trials (see Fig. 4). In order to examine the change of success rates from the earlier to the later practice trials, a linear regression on the daily success rate for the 5 days practice was used to derive the slope of the rate change. And, an independent sample t-test was used to examine the difference between the SOC group and the PID5 group. The result showed a larger drop of success rate for the PID5 group than the SOC group but did not reach the significant level, $t(12) = -1.38$, $p = .096$. However, a moderate effect size was observed ($d = 0.74$) for this comparison.

The result of the 2 (Post Test) × 3 (Group) mixed ANOVA on the improvement rate showed a significantly higher improvement rate of the two weeks post-test than the immediate post-test, $F(1, 18) = 10.71$, $p < .01$, but no significant group effect, $F(2, 18) = .07$, $p > .05$ nor interaction (see Table 4). Table 4 shows there were several participants who had a "negative" improvement rate in the two post-tests, especially participant R7 of the SOC group who had negative improvement rates for both post-tests. Considering the individual practice performances, it was found that participant R7 in the SOC group had a very different practice strategy, namely, very few successful trials followed

Table 4
Individual improvement rates of the 2 post-tests for the 3 groups.

SOC	Individual participant						
	R1	R2	R3	R4	R5	R6	R7
POST1	0.27	0.31	0.47	0.27	0.19	0.23	−0.11
POST2	0.34	0.34	0.59	0.34	0.10	0.28	−0.03
PID5	51	52	53	54	55	56	57
POST1	0.20	−0.06	−0.03	0.19	−0.11	0.12	0.00
POST2	0.11	0.00	0.10	0.19	0.03	0.20	0.00
PID20	201	202	203	204	205	206	207
POST1	−0.05	0.38	0.50	0.12	−0.12	0.12	−0.06
POST2	0.05	0.34	0.53	0.19	−0.01	0.10	0.10

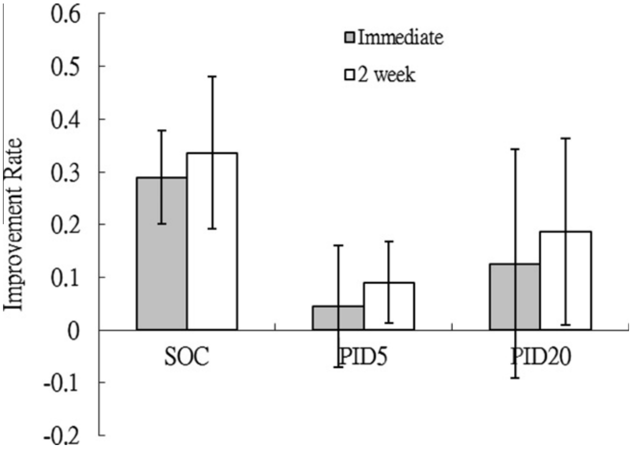

Fig. 5. Mean improvement rate (with between-participant SD) as a function of test session (immediate and 1 week) and practice condition (SOC, PID5, PID20).

by very long strings of unsuccessful trials, a strategy that was not observed in any other participants of the SOC group. One of the unique and advantageous features of the SOC schedule is that the performer had a chance to get out of the repeated experience of failure by choosing to increase the initial speed of the ball and this option was frequently used by all but participant R7 in the SOC group. In order to test whether the unusual strategy adopted by participant R7 influenced the overall performance of the SOC group, the ANOVA tests were performed again excluding participant R7 in the SOC group.

The results of improvement rate analysis excluding participant R7 showed a significant group effect, $F(2, 17) = 4.18$, $p < .05$, and the Scheffé post hoc comparison revealed a higher improvement rate for the SOC group than the PID5 group ($p < .05$). The 2-week post-test remained a significantly higher improvement rate than the immediate post-test results, $F(1, 17) = 9.05$, $p < .01$ (see Fig. 5). No interaction effect was found significant.

4. General discussion

The findings from the two experiments show that the self-organized criticality (SOC) learning group adopted an adaptive strategy (Proctor & Dutta, 1994) where success and failure in the task tended to maximum levels of uncertainty, namely 50%. The progressively increasing difficulty (PID) groups had a much lower success rate than the SOC group a finding that is consistent with the notion that the level of uncertainty may have influenced the motivation of the performers (Atkinson, 1957). Although the practice strategy of the PID groups in the two experiments also belongs to the adaptive learning category, it did not allow the participants to go back to an earlier difficulty level, so there were times when continuous failure occurred for hundreds of trials and the learner could do nothing but continue trying the unsuccessful, difficult task. It is conceivable that after many unsuccessful trials, not only motivation but the learning dynamics that once carried the successful performances could not be reproduced.

The influence of a low success rate was reflected in the negative improvement rate of the post-tests. There were 7 participants who had negative improvement rates in one or both of the post-tests from experiment 2. Examining their average success rates, the 3 participants in the PID20 group all had a daily success rate below .1 and all 3 had almost 0 success rate for the last 200 trials. For the PID5 group, the one participant who had the negative improvement for the immediate post-test and a 0 improvement for the 2-week post-test performed the lowest daily success rate of .22 in the group and the daily success rate of the last 4 days further decreased to .16. The other 2 participants of PID5 group who had negative improvement in the immediate post-test also had a relatively low daily success rate and one of them had 0 success rate for the last 100 trials. Of course, it is possible that with more trials of practice in a session that these learners would have improved their performance by realizing more successful trials but that is an empirical question.

The self-paced SOC learning group not only had a 50% success rate that was also higher than the PID groups, but the variability of the success rate was also lower indicating a consistent success rate over practice days. For the PID conditions, the lowest increased difficulty of 5% led to a better success rate because the slow increase of the difficulty level provided more successful trials earlier in practice. However, the smaller steps of difficulty increment did not help to make a large improvement for the post-tests. The difficulty increment of 10% and 20% PID conditions had just the opposite trend where large steps of difficulty increment during practice often resulted in a few successful trials after a long string of failure attempts that led to the lower success rate. Thus, the percentage of the increased difficulty in the learning strategies seems to have differential effects on both short term (adaptation) and long term (learning) performance. The theoretical claim that a consistent 50% success rate is optimal in learning the roller ball task in terms of the improvement rate was supported by the findings of the SOC condition in these experiments but clearly further experimentation is required on this issue.

It appears that the SOC practice condition by scaling task difficulty to skill level in a self-controlled adaptive strategy (Proctor & Dutta, 1994) kept the participants close to the parameter region of the transition. Thus, in this self-organized practice condition learners can, in effect, use task difficulty as a control parameter to increase the probability of a successful outcome in motor learning. This finding also supports the proposition that there is duality to difficulty and skill in that a successful outcome can be sustained at a given probability level by scaling the reduction of the ball speed to the enhanced skill level of the learner (Newell, Liu et al., 2009). Although the difficulty level is increased with a decrease of initial ball speed, the increment of difficulty is probably not linear and has not been identified as any known function (Liu et al., 2006).

Although most of the participants in the SOC group adopted a strategy that approximated a 50% rate of success and failure, there were other strategies adopted in the SOC group. An example is the one participant who did not change the difficulty level at all. This participant told the experimenter that she felt comfortable staying in just that initial speed and that she did not want to advance to a higher difficulty level. This observation provides support to the position that motivation to improve is a most important factor that influences the effect of self-controlled learning strategy (McCombs, 1989). Another example is from the SOC condition of Experiment 2 where the learner exhibited a difficulty distribution pattern similar to the PID group. As a result, this learner had negative improvement rates for both post tests. These particular individual learning strategies also point up that self-discovery learning situations afford a wider range of learner strategies than under directed learning environments (Kornell & Bjork, 2007; Vereijken & Whiting, 1990), and that some of these self-selected strategies may not be effective (Choi, Qi, Gordon, & Schweighofer, 2008). Finally, the generality of the effects shown here for the effectiveness of the manipulation of task success and failure remains to be determined but whatever the behavioral context of the phenomenon at hand it should be recognized that the effects shown here are related to a task that has a phase transition.

There was an unexpected but interesting finding in Experiment 2 where the improvement rate for all practice conditions was higher at the 2-week post-test than the immediate test. This is not a typical outcome for motor learning research (Holding, 1965; Proctor & Dutta, 1994) but is consistent with recent studies of the beneficial effects of the additional time duration between practice sessions for the consolidation of memory formation in the acquisition of new motor task (Shea, Lai, Black, & Park, 2000; Wixted, 2004), where memories are more stable after consolidation than before. Clearly, this time duration between session effect on motor learning warrants further study including whether it interacts with instructor and self-controlled strategies for learning.

There are a number of practice regimen manipulations that are related to the SOC condition implemented here and this is a direction for future research. These include practice strategies whereby the learner stays longer at a difficulty level than seems necessary and in contrast a flexible strategy where the learner switches to another approach after very few trials at that condition. These sub groups of SOC condition showed an overall success rate close to 50%. However, different sub groups had different characteristic strategies that tended to be over or under the 50% success rate approximation. It remains an empirical question as to whether these specific strategies would have different short term and long term effects on the roller ball performance. The findings from this study also open the question as to whether the effectiveness of practice schedules is different in tasks that require the learning of a new parameter scaling (the standard tasks studied in motor learning) from those that require a transition of coordination mode to be successful in the task (Newell, 1985). At this point we have little knowledge of practice schedule effects in this latter class of tasks that hold so much relevance to many contexts in motor learning and development.

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