Many studies have examined how stress or anxiety affects motor performance. A major theory proposed by early researchers was the inverted-U hypothesis, which was based on the general arousal concept. However, it has been criticized from various viewpoints, for example the failure to explain the mechanism, the lack of clear empirical support, and the face validity of the curve shape (see Jones, 1995; Neiss, 1988, for reviews).

An appealing alternative theory is the conscious-control theory (Baumeister, 1984; Hardy, Mullen, & Jones, 1996; Masters, 1992; Willingham, 1998), which proposes that performers under stressful conditions consciously attempted to control their movements, disrupting the automaticity of control. Twenty-two male subjects (11 in Experiment 1 and 11 in Experiment 2) performed an underhand ball-throwing task using the non-dominant hand. The inter-trial variability of two kinematic measures was analyzed, namely arm-joint coordination during the throw and hand position at release (release point). Experiment 1 confirmed the validity of regarding these variability measures as indices of automaticity, as they did not vary in spite of resource shortage induced by a dual-task paradigm. In Experiment 2, in which stress led to a detriment in performance, the variability of joint coordination increased, whereas the release point became more fixed. These findings imply that throwing performance is impaired when the coordination is disrupted as a result of inflexible movement executed by conscious control.

Key words: stress, underhand throwing, automaticity, variability, joint coordination.
that stress impairs the quality of performance because task-irrelevant information competes with task-relevant information for space in the processing system (Eysenck, 1982, p. 99). This proposition seems plausible, and is supported by many empirical data (e.g., Darke, 1988; Leon, 1989; MacLeod & Mathews, 1988; Rapee, 1993; Sorg & Whitney, 1992). Based on this theory, poor performance is not brought about by deautomatization, because automaticity requires few, if any, resources. For example, Masters’ (1992) subjects, who had explicit knowledge, performed poorly because they could not effectively execute conscious control, owing to the resource shortage.

The present study tested the critical prediction of the conscious-control theory. It examined whether stress impairs automaticity, thus leading to poor performance. The problem here is the difficulty of identifying behavioral indications of automaticity. One index might be movement variability. It has been widely accepted that, at least in early stages of learning, skilled movements that involve automaticity are highly stable (e.g., Lee & Swinnen, 1993; Logan, 1985; Platz, Dentzler, Kaden, & Mauritz, 1994; see Vereijken, van Emmerik, Whiting, & Newell, 1992, for evidence). Thus it is expected that automaticity can be measured using movement variability. The validity of this idea was examined in Experiment 1.

The experimental task in the present study was underhand ball throwing with the non-dominant arm, while aiming at a target. All the subjects were right-handed. It should be noted that the degree of freedom is constrained only in the early stages of learning: In later stages it is freed to obtain flexible movement (see Newell & McDonald, 1994; Vereijken et al., 1992). The non-dominant hand was therefore chosen, so that low movement variability would represent high degree of automaticity. In order for subjects to acquire the skill quickly, the relatively simple underhand ball throw was used in preference to more complex types of throwing skills, such as overhand throwing or free throwing as in basketball. The subjects threw tennis balls. The target, composed of four concentric circles, was fixed on a wooden board (100 cm × 100 cm). The diameter of the inner circle (the bull’s-eye, at which the subject aimed) was 8 cm and the diameters of the other circles increased by 16-cm intervals. The board was placed so that the bull’s-eye was at a height of 1 m and at a distance of 3.3 m from the subject. Two LEDs were placed over the target in order to pace the
throwing task. A red LED that was activated for 1.5 s alerted the subjects to prepare for a trial, and it was followed by a green LED that signaled the start of the trial. Activation of both LEDs was accompanied by audible beeps.

The displacement of the arm joints was recorded with a Hi-8 video-camera (SONY, Tokyo, Japan), which was placed 3 m to the left of the subject and at a height of 1 m. The target was filmed with a 8-mm video-camera (SANYO, Tokyo, Japan) placed behind the subject, to ascertain subjects’ performance.

To identify the frame in which the ball was released, a small piece of folded plastic (3 cm × 1 cm) was placed at the middle phalangial joint of the middle finger. Copper plates were attached to the inner sides of the fold. When a tennis ball was being held, the copper plates touched each other, and the electrical circuit was completed. This activated an LED located behind the subject’s head, and this was also monitored by the camera monitoring the arm movement. The frame in which the LED was deactivated indicated ball release.

**Procedure.** LEDs were attached to the shoulder, elbow, wrist, hand and hip, at specific anatomical locations: the acromion process, lateral epicondyle, radius styloid process, index ungual phalange, and iliac crest, respectively. These were used to calculate joint angles.

The subjects were instructed to aim and throw the ball at the bull’s-eye, as accurately as possible. Subjects performed the throwing task in two sessions: a practice session and a performance session. The practice session consisted of 5 blocks of 30 trials, with 3–5-min rest between the blocks. The performance session, which consisted of a single block of 30 trials, was a dual-task session in Experiment 1 and a stress session in Experiment 2.

**Data analysis.** Data were collected for only the first and last 10 trials of the practice session, together with the first 10 trials of the performance session. The practice-session trials were called the pre-practice session, the post-practice session, respectively. The kinematic data were sampled for 3 s. The displacement of LEDs was digitized at a sampling frequency of 60 Hz and processed via a two-dimensional movement-recording system (Quick-MAG system 1, OKK Inc., Tokyo, Japan). Van Rossum and Bootsma (1989) reported that the arm movement in underhand throwing was executed mainly in the sagittal plane. Therefore, two-dimensional recording was sufficient for accurate analyses. After transfer to the life-size unit, these data were filtered by using a Butterworth lowpass filter. The filtered frequency was 2.4–4.8 Hz, which was determined by Hinrichs’ (1982) technique.

Performance was evaluated in terms of absolute error (AE) and variable error (VE). The AE was the mean absolute distance from the bull’s-eye to the point of ball impact. The VE was the standard deviation of the AE (see Schmidt, 1988, ch. 3).

The variability of joint coordination was evaluated as the standard deviation of cross-correlations with zero time delay between the angles at the shoulder, elbow and wrist (see McDonald et al., 1989; Vereijken et al., 1992). Cross-correlations were calculated for both angular displacements and angular velocities. The cross-correlations range from 1 to –1. A value close to ±1 means that changes in one cross-correlated component are highly dependent on changes in the other, while a value close to 0 means these components change independently. Cross-correlation analysis was performed on the data for the angular displacement and velocity during the forward arm swing, which started at the end of the back swing (termed takeback), and terminated at the moment the ball was released (see Figure 1). Each joint angle was defined as the angle between two segments. The shoulder angle, for example, was an angle between the trunk (from the hip LED to the shoulder LED) and the upper arm (from the shoulder LED to the elbow LED).

---

2 The amount of practice was determined in a pilot experiment, with a criterion that it was enough to decrease the variability of joint coordination. Four male subjects performed 300 throws on two consecutive days (150 throws each day). The procedure was the same as in Experiments 1 and 2. The variability decreased up to around 150 throws, but then remained more or less constant, although this was not tested statistically.
The variability of the release point was represented by the standard deviation of the horizontal and vertical positions of the hand when the LED that indicated the ball release was deactivated.

**Experiment 1**

The purpose of Experiment 1 was to examine whether the degree of automaticity could be measured using the variability of the kinematic measures. If the variability is determined by the degree of automaticity, it should not increase in the case of resource shortage for motor control. In the present experiment, a situation of resource shortage was artificially created by a dual-task paradigm, in which subjects performed the throwing task at the same time as a memory task. The variability measures should not change in the dual-task situation, despite a worsening of performance, because, as Singer, Lidor, and Cauraugh (1993) demonstrated, a conscious strategy cannot be executed effectively when mental resources are allocated to the processing of a secondary task.

**Method**

**Subjects.** The subjects were 11 male volunteers, ranging in age from 19 to 28 years. All were right-handed.

**Secondary task.** The secondary task was to memorize a random sequence of five one-digit numbers (e.g., 5, 4, 7, 1, and 8), and to reproduce the number sequence backward immediately after the trial. The numbers were randomly selected from numbers 1 to 9, with a restriction that the same number did not appear more than once in a sequence. The numbers were recorded with a woman’s voice and presented using a personal computer (APTIVA 2134 J3X, IBM, Tokyo, Japan).

**Procedure.** In the practice session, subjects learned the throwing task without the simultaneous secondary task. In the performance session, subjects performed the throwing task as well as the secondary task. After the ready signal, the five digits were presented. The start signal was activated during the presentation of digits, so that the subjects had to begin the throwing task as the digits were being presented. The start signal was activated in an interval between the digit presentation, so that the subjects were not prevented from hearing the digit by the audible beep of the start signal.

**Results**

**Performance scores.** Table 1 shows mean performance scores. A one-way analysis of variance (ANOVA) with repeated measures, conducted on the AEs and VEs separately, revealed a significant main effect of the session in the AE, $F(2, 20) = 29.84, p < .01$, and in the VE, $F(2, 20) = 16.23, p < .01$. A post-hoc analysis showed that both the AEs and the VEs were reduced significantly in the post-practice
session and increased significantly in the dual-task session.

Variability of joint coordination. Figure 2A shows the mean within-subject variability, which was represented by the standard deviation of cross-correlations for angular displacement. A two-way repeated measures ANOVA (3 coordinations × 3 sessions) revealed neither a main effect of session nor an interaction between coordination and sessions, $F(2, 20) = .24, ns$ and $F(4, 40) = 1.42, ns$, respectively.

Figure 2B shows the variability of cross-correlations for angular velocity. An ANOVA revealed that there was a marginally significant interaction, $F(4, 40) = 2.39, p < .07$. Post-hoc analysis revealed that the standard deviation in the post-practice session was increased for the shoulder-elbow coordination, and decreased for the shoulder-wrist. However, these values did not significantly change in the dual-task session.

Variability of release point. Variability of the release point, represented by the standard deviation, was calculated for horizontal and vertical positions separately. Mean variability scores in the pre-, post- and dual-task sessions were 4.92, 3.77 and 3.45 cm for the horizontal position, 5.27, 5.12 and 4.52 cm for the vertical position, respectively. A one-way ANOVA with repeated measures was conducted for each position separately and showed no significant effects, $F(2, 20) = 1.53, ns$, $F(2, 20) = .90, ns$, respectively.

Discussion

The purpose of Experiment 1 was to examine the effect of resource shortage induced by the secondary task on the kinematic variability. It was assumed that if the variability was determined by the degree of automaticity, the kinematic measures would not vary in the dual-task situation. The results revealed that the kinematic variability was not affected by the simultaneous secondary task, in spite of the performance decrement. Therefore the kinematic variability can be regarded as an index of automaticity.

**Table 1.** Mean (SD) absolute errors (AEs) and variable errors (VEs) on the performance scores in Experiment 1

<table>
<thead>
<tr>
<th>Error</th>
<th>Pre-practice</th>
<th>Post-practice</th>
<th>Dual task</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE</td>
<td>25.5 (6.06)</td>
<td>12.0 (2.85)</td>
<td>17.6 (4.42)</td>
</tr>
<tr>
<td>VE</td>
<td>12.1 (1.31)</td>
<td>7.1 (1.70)</td>
<td>10.4 (2.80)</td>
</tr>
</tbody>
</table>

**Figure 2.** Mean within-subject variability of cross-correlations for angular displacement (A) and angular velocity (B) in Experiment 1.
However, it must be noted that kinematic variability did not reduce significantly after the 150 throws, regardless of the performance improvement. The outcome did not conform to the expectation that the subject would stabilize the movement to restrict degrees of freedom (Vereijken et al., 1992). Therefore it can be said that the kinematic variability did not necessarily correlate with performance variability.

**Experiment 2**

The purpose of Experiment 2 was to examine the effect of stress on the two variability measures, which were regarded as indices of automaticity from the findings in Experiment 1. If stress impairs automaticity, the degree of freedom of movement, which was constrained through practice, will be freed because of deautomatization. As a result, consistent movement will be broken and the inter-trial variability of joint coordination and release point will increase.

**Method**

**Subjects.** Eleven subjects with high trait-anxiety scores on a Japanese version (Shimizu & Imae, 1981) of the STAI (Spielberger, Gorsch, & Lushene, 1970) were selected, in order to see performance impairment clearly (e.g., Calvo & Alamo, 1987; Terelak, 1990). The 11 male volunteers (aged 18–23 years), whose mean STAI trait score was 43.6 (SD 4.8), were all new to the experimental task.

**Procedure.** In the performance session, the subjects performed a throwing task under evaluative stress. Before the performance session, the subjects were instructed that this experiment was one of the most important parts of the project, which was taken seriously by many professors. The importance of accomplishing two particular goals in the next block was stressed: to improve their scores from previous blocks, and to be sure to throw the ball within the outer perimeter of the circular target in every trial (the radius of the outer circle was 28 cm).

<table>
<thead>
<tr>
<th>Table 2. Mean (SD) absolute errors (AEs) and variable errors (VEs) on the performance scores in Experiment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>AE</td>
</tr>
<tr>
<td>VE</td>
</tr>
</tbody>
</table>

**Results**

**Performance scores.** Table 2 summarizes performance in the throwing task. A one-way ANOVA with repeated measures was conducted on the AEs and the VEs separately, and revealed a significant main effect of session on both the AE and the VE, $F(1, 10) = 22.80$, $p < .01$, $F(1, 10) = 14.84$, $p < .01$, respectively. Post-hoc analysis showed that the AE was reduced significantly in the post-practice session and was increased significantly in the stress session. The VE was reduced in the post-practice session but did not change significantly in the stress session.

**Variability of joint coordination.** Figure 3A shows the mean within-subject variability of the cross-correlations for angular displacement. A two-way ANOVA with repeated measures revealed that there was a marginal main effect of session, $F(2, 20) = 2.81$, $p < .10$. Post-hoc analysis found a significant tendency for an increase in the stress session ($p < .05$). Figure 3B illustrates the mean within-subject variability of the cross-correlation for angular velocity. A main effect of session, $F(2, 20) = 3.76$, $p < .05$, was significant. There was a significant decrease in the post-practice session and a significant increase in the stress session.

**Variability of release point.** Mean variability scores in the pre-practice, post-practice, and stress sessions were 4.26, 3.60 and 2.51 cm for the horizontal position, 5.40, 4.71 and 3.82 cm for the vertical position, respectively. An ANOVA with repeated measures showed that a main effect of session was significant in the horizontal position, $F(2, 20) = 5.25$, $p < .05$. The variability score in the stress session was lower than that in the pre- and post-practice session.
Discussion

The purpose of Experiment 2 was to examine the effect of stress on the variabilities of the two kinematic measures in throwing, namely the joint coordination in the arm and the hand position at the point of releasing the ball. These variabilities were regarded as indices of the automaticity from the findings in Experiment 1, in which the variabilities did not change in spite of the performance decrement caused by the resource shortage for motor control.

The conscious-control theory and the resource-shortage theory predict different effects of stress on these variabilities. The former theory predicts a harmful effect because it proposes that stress leads to deautomatization and thus interferes in learned stability of the movement. In contrast, the latter theory predicts no harmful effects because even if stress reduces the resources available for motor control, the kinematic variabilities do not change in the case of resource shortage.

The result of variability in joint coordination supports the conscious-control hypothesis. Kinematic variability, which was represented by the standard deviation of cross-correlations, was significantly increased in terms of angular velocity and was marginally increased in terms of angular displacement.

However, the result of variability in the release point was not in line with the predictions of either theory. The variability in the horizontal position decreased significantly in the stress session, despite a decline in throwing performance. This result is somewhat surprising, because in many studies the consistent release position has been highly correlated with skilled throwing (e.g., Hore et al., 1994, 1995; Hore, Watts, & Tweed, 1996; McDonald et al., 1989).

Did the subjects consistently reproduce only the release point, or the whole hand trajectory? Figure 4 shows a comparison of the trajectories of four subjects in the post-practice and the stress session. It seems that not all of the hand positions throughout the arm swing had become stable by the stress session. To confirm this visual inspection statistically, the variability of hand position at the takeback was further analyzed as a representation of the trajectories. Mean variability scores in the post-practice and stress sessions were 3.34 and 2.83 cm for the horizontal position, and 1.58 and 1.37 cm for the vertical position, respectively. A one-way ANOVA with repeated measures showed no difference between the sessions. This suggests that not all of the hand positions throughout the swing of the throw were stabilized under

![Figure 3. Mean within-subject variability of cross-correlations for angular displacement (A) and angular velocity (B) in Experiment 2.](image-url)
stress. One would expect the subjects to conform to the conscious-control mode especially in reproducing consistent release.

**General discussion**

Past studies that support the conscious-control theory have a problem in that the results can also be explained by the resource-shortage theory. However, in this study it is hard to justify the results from the viewpoint of the resource-shortage theory. In Experiment 1 the variability of kinematic measures did not change even when the resources available for motor control were reduced.

The conscious-control theory offers a more plausible explanation of the results, although it does not explain them entirely. According to this theory, the desire to perform well causes a subject to use conscious control because it can increase accuracy (see Willingham, 1998).

In Experiment 2, the subjects were instructed to throw as accurately as possible in the stress session. To accomplish the goal, one might expect the subjects to attempt to reproduce their movement by conscious control. This tendency was reflected in the consistency of the release point. However, the accomplishment of accurate throws (invariant position of ball release) by conscious execution disrupted the invariance in joint coordination, and this may explain the subjects’ poor performance.

If these interpretations are true, the results also suggest that the conscious-control theory needs revision. In Experiment 2, the hand position at ball release was initially inconsistent, but became stable through practice. The theory predicts the hand position should become variable again under stress, because the movement regresses to that in the early stages of learning. However, in the stress session hand position became more stable.

---

although throwing performance was impaired. Therefore the change from automatic to conscious control does not mean regression to the initial stages of learning. Considering that consistent release is usually critical for throwing performance, the change to conscious control reflects adherence to a control strategy that the performers think is critical for better performance.

Although the results support the conscious-control theory, it must be noted that conscious control itself does not have a detrimental effect on motor performance. Some earlier findings have suggested the usefulness of the conscious strategy on motor control or learning. For example, augmented feedback about movement kinematics is reported to have improved skill learning (e.g., Schmidt & Young, 1991; Todorov, Shadmehr, & Bizzi, 1997). Dadkhah (1998) showed that increasing the body consciousness of disabled sportsmen helped them to attain better body balance. Notably, according to Bäckman and Molander (1991), the adoption of a conscious-control strategy did not necessarily impair the performance of highly skilled players. These findings imply that whether conscious control disrupts performance under stress or not depends on the interaction between the demand of the skill (e.g., speed, timing) and the degree of skill (e.g., expert or novice).

Conclusion

The present study tested the conscious-control theory, by examining the effect of stress on automaticity of motor control. In addition to a worsening of performance, the consistency of joint coordination was disrupted, while the release point was fixed. The results support the conscious-control theory, although the results concerning the release point call for a revision of the theory. One possibility is that the effort to throw accurately caused the subjects to control the release point consciously, because they thought that the release point was the most important factor influencing the accuracy of ball direction. Conversely, though, the use of conscious control disrupted the more dynamic joint coordination. Therefore the variability of joint coordination increased, resulting in a decrement in performance.

References


(Received Feb. 12, 1999; accepted Jan. 22, 2000)