

Relation of Repetition Effect and Response  
Programming in Serial Reaction Time

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**Dedicated to the late Professor Iwao Matsuda  
who profoundly influenced my life**

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## CHAPTER 1

### INTRODUCTION

In many movement situations, performer must try to respond as quickly and accurately as possible in a complex and constantly changing environment. Success in these situations seems to be determined not merely by performers' physical abilities but also by their cognitive skills associated with handling the environmental information and adapting the behavior to the changing environment. An ultimate example of this success can be seen in player's excellent performance in professional sports. Recall the 2002 FIFA World Cup. England's midfielder David Beckham dribbles past opponent defenders at top speed while looking for available passing options and makes his pinpoint pass to a striker. Brazil's striker Ronaldo picks up the ball from a teammate, shakes off his marker, dribbles into the penalty area and makes a beautiful goal. Germany's goalkeeper Oliver Kahn punches away the ball approaching at 100 km per hour with his one hand at full stretch to his right, under pressure with opponents trying to restrict both the time and space available to perform. How are these quick and correct performances achieved in a complex and constantly changing environment? What is the nature of mental processes underlying these performances?

Although many cognitive psychologists and sport psychologists have been trying to understand how humans handle environmental information, the most important contributions to an understanding of this mental process comes from studies using an information-processing approach. In this approach, the human is viewed as a processor of information much like a computer in which information is encoded, stored, retrieved, transformed, and acted on. The underlying assumption of this approach has been that

serial and nonoverlapping processing stages exist between a stimulus and a response. To test this assumption, much of researchers have typically adopted a reaction-time (RT) paradigm. RT is defined as the interval of time between the onset of a stimulus and the initiation of a response. With this RT paradigm, it is assumed that a RT is composed of the sum of a number of processing times, each of which is consumed by a processing stage involved in the translation of a reaction stimulus into a response. Thus, longer RT is supposed to reflect longer delays in information processing in one or more of the stages (Sanders, 1998; Schmidt & Lee, 1999).

There are several types of RT situations. One type of RT situation is simple RT, where the subject is informed about which response will be required in advance but has to wait for a reaction signal. Another type of RT situation is choice RT, where the subject is informed in advance that one of a number of possible responses will be required but has to wait for a signal indicating which response should be executed. The third type of RT situation is discrimination RT or go/no-go RT, where the subject is informed in advance that a response will either be required or not and has to wait for a signal indicating whether or not to execute the response.

Although several methods have been developed to discover processing stages using RT paradigm (for reviews see Meyer, Osman, Irwin, & Yantis, 1988; Sanders, 1998), one of the most influential methods has been the additive-factor method developed by Sternberg (1969). In this method, the researcher manipulates several factors and determines whether the factors have additive or interactive effects on RT. If two factors have additive effects, two different processing stages are likely to be involved, because under the serial stage, RT is a sum of the component stage duration. Alternatively, if two factors have interactive effects, they are assumed to affect the same processing stage, because the size of the effect of the factor depends on the state of the other. Based on this logic, by manipulating various factors and observing patterns of additivity and interaction, it is possible to infer how many different processing stages exist and what the stages do. The use of the additive-factor method requires the

assumption of sequential stages for which the processing at one stage must be completed before the processing at the next stage begins. Although it has been pointed out that several processes of information processing may take place in a parallel contingent fashion, not in a serial fashion (e.g., McClelland, 1979), the additive-factor method has proved to serve as a credible tool in discovering processing stages (Meyer, et al, 1988; Sanders, 1998).

At least three processing stages have been proposed that intervene between the presentation of a stimulus and the initiation of a response. The first stage, termed the *stimulus-identification stage*, concerns the perceptual processes (or perceptual processing), such as stimulus detection and pattern recognition. In this stage the performer must sense that a stimulus occurred and make sense of it. Variables that affect the duration of processing in this stage include the intensity, clarity, and familiarity of the stimulus (e.g., Posner, 1964). A second stage, termed the *response-selection stage*, concerns response selection and decision processes. In this stage, after the important features of the stimulus have been properly identified, the performer must decide on an appropriate response. Variables that affect the duration of processing in this stage include the number of stimulus-response alternatives and the compatibility of the stimulus and response (e.g., Fitts & Seeger, 1953). The final stage, termed the *response-programming stage*, concerns the processes of movement preparation. After the stimulus has been identified and the response has been selected, the primary task in this stage is to translate this abstract idea into a set of muscular actions that will achieve the response. Variables that affect the duration of processing in this stage include movement complexity, the number of movement parts, accuracy demands of the movement, and movement duration (e.g., Klapp, 1996; Schmidt & Lee, 1999).

Typically, in experiments using the RT paradigm, each trial is comprised of the presentation of a reaction signal and the execution of a response, followed by the next trial with plenty of intertrial interval. Thus, the event involved in a trial is hardly influenced by that involved in a preceding trial. However, Bertelson (1961), who was

concerned with reactions in real-life situations, questioned the ecological validity of the results obtained from this RT procedure. It seemed to him that in real-life situations that demand a quick and adaptable response in a constantly changing environment, humans do not respond to isolated signals but to sequence (or context) of signals. To solve this problem, he adopted a serial responding task in which subjects are required repeatedly to execute the correct responses for signals that are presented in rapid succession. The most important finding obtained from his experiment was that RT is shorter when the same stimulus is repeated than when a different stimulus is presented. Since the influential study done by Bertelson (1961), this phenomenon, termed the *repetition effect*, has been known as one of the most robust phenomena in traditional RT experiments. The repetition effect is thought to reflect basic mechanisms that underlie many everyday skills and skill acquisition. Because of their importance to understanding human skills, attempts have been made to identify the stage (locus) of the information processing facilitated by repetition. Although several hypotheses have been proposed, thus far, the most prominent view has been that the primary locus of the repetition effect is response selection (e.g., Pashler & Baylis, 1991b).

As mentioned earlier, however, there is another central process associated with the preparation of response, which occurs after response selection and precedes the execution of motor response. This process is referred to as *response programming*. Surprisingly, despite the abundant evidence for response-programming stage, any research efforts have not been directed toward investigating the involvement of response-programming stage in the repetition effect. Therefore, the present doctoral research constitutes an attempt to identify further the locus of the repetition effect. More specifically, the present study is conducted to examine the possibility that the repetition effect occurs at the stage of response programming.

This article is organized into six chapters. The next chapter reviews the literature on the repetition effects in serial reaction tasks and evidence for the existence of response programming and motor program. In Chapter 3, the possibility that the

repetition effect occurs at the stage of response programming is suggested and four experiments conducted to test this hypothesis are described. Chapter 4 addresses questions of whether the repetition effect that arises from response programming is due to a speedup of the processing or bypassing of the processing and how long the repetition effect that arises from response programming is retained, by conducting two experiments. Chapter 5 examines whether or not the repetition effect that stems from response programming occurs when responses are imagined as well as when responses are actually performed, by conducting two experiments. Finally, the findings of eight experiments conducted in this study are summarized and discussed in Chapter 6.

## CHAPTER 2

### REVIEW OF LITERATURE

This review is organized into three main sections. The first section provides a brief explanation of repetition effects in serial choice RT tasks. The second section reviews early and recent studies on locus of repetition effects. In the third section, research is presented which suggests the existence and functions of response programming and motor programs.

#### Repetition Effects in Serial Choice RT Tasks

In a serial choice RT task, the RT for a repeated stimulus is shorter than for a nonrepeated stimulus which is different from the immediately preceding one (Bertelson, 1961, 1963, 1965; Campbell & Proctor, 1993; Keele, 1969; Kirby, 1972; Kornblum, 1967; Pashler & Baylis, 1991b; Peeke & Stone, 1972; Rabbitt, 1968; Smith, 1968). This phenomenon was first reported in Bertelson's (1961, 1963) RT study. He had subjects perform a two-choice task in succession in which the correct response was right keypress response for right lamp and left keypress response for left lamp. In this serial choice reaction, thus, the four possible stimulus patterns were right-right and left-left (repeated stimulus), and right-left and left-right (nonrepeated stimulus). He found that the RT for the repeated stimulus was 70 msec. shorter than for the nonrepeated stimulus. Moreover, when stimulus-response relation was changed so that the correct response was left keypress response for right lamp and right keypress response for left lamp, the RT for the repeated stimulus was 110 msec. shorter than for the nonrepeated stimulus.

Bertelson has named this RT phenomenon the repetition effect.

It has been shown that the repetition effect was influenced by a number of variables. In general, the repetition effect increases with the number of alternative stimuli and responses (Bertelson, 1961; Kornblum, 1967, 1973). The effect is larger for incompatible stimulus-response relations than for compatible stimulus-response relations (Bertelson, 1963; Rabbitt & Phillips, 1967; Schvaneveldt & Chase, 1969). In addition, the repetition effect depends on response-stimulus interval or intertrial interval. The size of the effect is particularly marked when the response-stimulus interval or intertrial interval is within 1 sec. (Bertelson, 1961; Bertelson & Renkin, 1966; Entus & Bindra, 1970; Hale, 1967), and decreases as the response-stimulus interval or intertrial interval increased. For example, Keele (1969) and Smith (1968) have found that the repetition effect decreases as the intertrial interval increased from 2 to 4 sec. With longer response-stimulus interval or intertrial interval beyond these intervals, there is no repetition effect, or instead the RT may be shorter for a nonrepeated stimulus than for a repeated stimulus (Williams, 1966). This phenomenon that the RT is shorter to a nonrepeated stimulus is referred to as *alternation effect* (Soetens, 1998). Two mechanisms have been proposed to explain all patterns of repetition effects and alternation effects: a strategiclike mechanism called *subjective expectancy* and an automaticlike mechanism called *automatic facilitation*. Kirby (1976) and Vervaeck and Boer (1980) suggested that the alternation effect is associated with subjective (cognitive) expectancy about the next stimulus, whereas the repetition effect is associated with automatic facilitation. Thus, the repetition effect cannot be avoided, and is not under subjects' control.

The question of interest here is: what is the nature of the repetition effect?

## Locus of Repetition Effects

### *Early Studies*

Since the influential study done by Bertelson (1961, 1963), several researchers have been trying to determine the locus of the repetition effect in the information-processing system. The underlying assumption has been that some aspects of the processing between stimulus and response proceed more quickly.

The focus of early research was merely on the question of whether the repetition effect is related to the repetition of the stimulus (central perceptual process) or the repetition of the response (peripheral response process). When each stimulus is assigned to a unique response as were manipulated in Bertelson's experiments (1961, 1963), however, it is not possible to determine the contribution of stimulus and response effects to overall repetition effect. This is because not only the stimulus but also the response is repeated in a repetition trial. To differentiate between these two possibilities, Bertelson (1965) introduced the information-reduction procedure. In this procedure several stimuli are mapped to each of several responses, so that both a given stimulus and response are repeated on successive trials (hereinafter called *stimulus repetition*) or the same response is repeated without repeating the same stimulus (hereinafter called *response repetition*). These conditions are compared with the condition in which neither stimulus nor response is repeated, thus, no repetition effect is expected (hereinafter called *nonrepetition*). It was assumed that if the response repetition showed a decrease in RT, then the repetition effect could occur at the stage of response execution; if only the stimulus repetition showed a decrease in RT, then the effect should be perceptual or central in origin.

Bertelson (1965) had subjects perform a two-choice task in which two even digits (2 and 4) were mapped to one keypress response and two odd digits (5 and 7) were mapped to the other keypress response. He found that RTs for stimulus repetition

and response repetition were approximately equal and both significantly shorter than for nonrepetition. He argued that the repetition effect is mainly related to peripheral response processes. Smith (1968) instructed subjects to press one key if the stimulus was either a digit 1 on a red background or a digit 2 on a green background, and the other key if the stimulus was either a digit 1 on a green background or a digit 2 on a red background. Under these conditions, RT was significantly longer for response repetition than for nonrepetition, whereas RT was significantly shorter for stimulus repetition than for either response repetition or nonrepetition. She concluded that the origin of the repetition effect is quite perceptual or central. Similar findings were also reported by Peeke and Stone's (1972), using color stimuli and form stimuli. Rabbitt (1968) performed an experiment in which the digits mapped to one keypress response were numerically higher than those mapped to the other keypress response. He also manipulated the amount of practice. He found that early in practice, RT for stimulus repetition was shorter than RTs for both response repetition and nonrepetition, which were not significantly different from each other. This finding is consistent with Smith's (1968) result, supporting a mainly perceptual locus of the repetition effect. Later in practice, however, the same results as Bertelson's (1965) were obtained, supporting a response-related locus of the repetition effect.

Thus, the results of early studies on the locus of the repetition effect were so contradictory that clear-cut conclusions were hardly extractable. The study of the repetition effect was popular for about 10 years, beginning in 1961, but interest waned during the 1980s.

### *Recent Studies*

In the early 1990s, the study of the repetition effect was revived by the emergence of Pashler and Baylis. The revival may have been due to developments in theoretical research on information processing stages during the 1980s.

Pashler and Baylis (1991b) have pointed out several problems on early studies of the repetition effect. One problem is related to the logic of the information-reduction procedure. The assumption made in the early studies was that if the response repetition showed a decrease in RT, then the repetition effect could occur at the stage of response execution. Another assumption was that if only the stimulus repetition showed a decrease in RT, then the effect could occur at the stage of perceptual processing. Pashler and Baylis (1991b) argued that the latter assumption might have been misleading, because only the stimulus repetition might show a decrease in RT even if the locus of the repetition effect was at response selection intervened between perceptual processing and response execution. As already mentioned, response selection refers to the information processing in which the response associated with the presented stimulus is selected. Pashler and Baylis (1991b) argued the need of the experimental design to isolate the contribution of perceptual processing and response selection.

A second problem is related to the categorizability of the stimuli used in the information-reduction procedure. Categorizability refers to the degree to which the stimuli share membership in a common conceptual category (e.g., Marcel & Forrin, 1974). Early studies differed in the results obtained, but they also differed in the categorizability of the stimuli used. In Bertelson's (1965) experiment, the digits 2 and 4 were mapped to one response and the digits 5 and 7 were mapped to the other response. In Rabbitt's (1968) experiment, the digits mapped to one response were numerically higher than those mapped to the other response. Both of these studies found significant stimulus and response repetition effects. It could be that Bertelson's and Rabbitt's subjects categorized the digits as even digits versus odd digits or low digits versus high digits. In Smith's (1968) experiment, on the other hand, the stimuli used hardly shared the membership in a common conceptual category, and no response repetition effect was found. Pashler and Baylis (1991b) argued that if the response repetition effect occurred only when a categorizable mapping of stimuli to responses was used, the effect might reflect a speedup of the processing between a stimulus category and a response category

rather than a speedup of response execution.

Pashler and Baylis (1991b) proposed five possible loci of the repetition effect based on the assumption that the effect originates in a speedup of the processing at the relevant stage (or stages) when the repeated event reuses the same processing as the previous trial. Figure 1 presents these possible loci proposed by Pashler and Baylis (1991b). In the task shown, subjects make a left key response by the right hand to any letter (letter a or letter A).

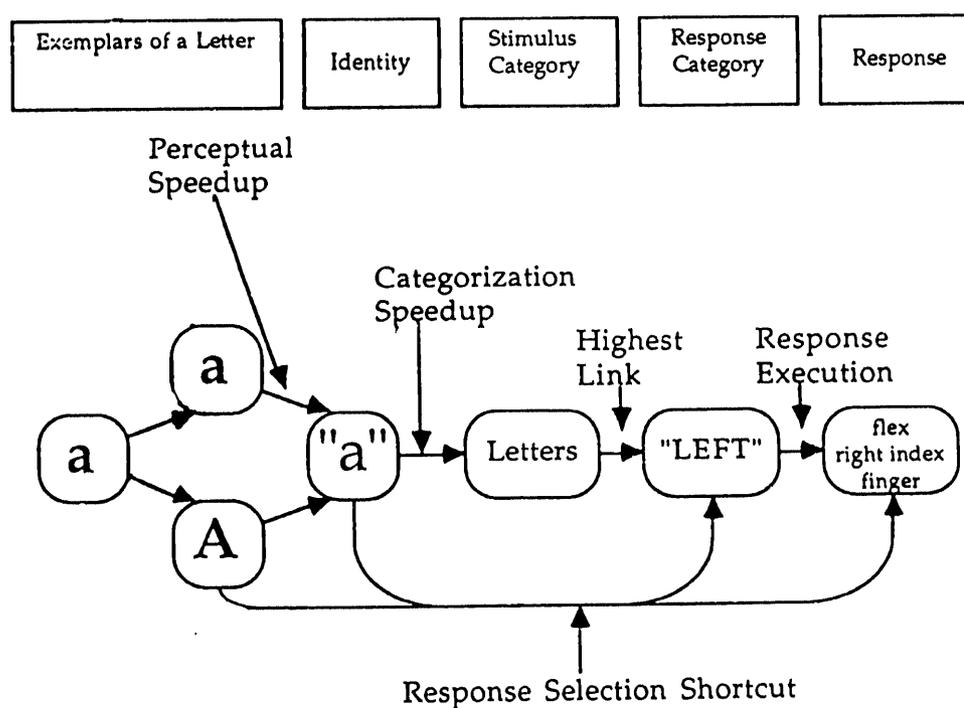


Figure 1. Possible loci for repetition effects proposed by Pashler and Baylis (1991b).

The first two hypotheses are related to the stage of stimulus identification. First, the repetition effect might originate in the perceptual processing between percept and stimulus identification (the perceptual speedup hypothesis). If this hypothesis is correct, then the repetition effect should occur only when the same physical stimulus is repeated (e.g., letter a and letter a). Thus, this hypothesis predicts that the repetition effect should

be found only for the stimulus repetition, regardless of whether the stimuli used are categorizable or noncategorizable. Second, the effect might originate in the processing of stimulus categorization as, for example, letters or digits (the categorization speedup hypothesis). If this hypothesis is correct, then the repetition effect should occur to different instances of the same characters (e.g., letter a and letter A). Thus, this predicts that the repetition effect should be observed for both stimulus and response repetitions only when the stimuli used are categorizable.

Several further hypotheses are related to the stage of response selection. One possibility is that the effect might arise from the processing between the stimulus category and the response category (the highest link hypothesis). If this hypothesis is correct, then the repetition effect should occur even when repeated responses share the same relative spatial relations (e.g., left keypress responses with the right hand and the left hand). Thus, this also predicts that the repetition effect should be observed for both stimulus and response repetitions only when the stimuli used are categorizable. Another possibility is that the effect might be located in the processing between the stimulus identification and the response (the response selection shortcut hypothesis). If this is correct, the repetition effect should occur only when the same physical stimulus and the same response are repeated. Thus, this hypothesis predicts that the repetition effect should be found only for the stimulus repetition, regardless of whether the stimuli used were categorizable or noncategorizable.

Finally, the repetition effect might originate in execution of motor response (the response execution speedup hypothesis). If this is correct, the repetition effect should occur only when the same motor responses are repeated. Thus, this predicts that the repetition effect should be observed for both stimulus and response repetitions, regardless of whether the stimuli assigned to a response were categorizable or noncategorizable.

To test these alternative hypotheses, Pashler and Baylis (1991b) conducted a series of experiments using Bertelson's (1965) information-reduction procedure. In their

experiments, letters, digits, or symbols such as & and # were used as stimulus categories, and were mapped to left, middle, and right keypress responses by the right hand in either a categorizable or noncategorizable mapping. For the noncategorizable mapping, one letter and one digit (e.g., letter P and digit 4) were assigned to each of the responses. For the categorizable mappings, on the other hand, the stimuli belonging to the same category (e.g., letter P and letter V) were assigned to each of the responses.

Pashler and Baylis (1991b) found no response repetition effects when a noncategorizable mapping was used (Experiment 1). When a categorized mapping was used, some benefit for the response repetition was found (Experiment 2 and 3). However, the size of response repetition effect was too smaller compared with that of the stimulus repetition effect. Both mapping conditions showed dramatic stimulus repetition effects. These findings were not consistent with the response execution speedup hypothesis. If this hypothesis were correct, the repetition effect should have occurred only with trials involving the same motor responses, regardless of whether the stimuli used were categorizable or noncategorizable. These findings did not also support both of the categorization speedup hypothesis and the highest link hypothesis. According to these hypotheses, the response repetition effect should have occurred only when categorizable mappings were used. This was not the case. In the experiment 4, they examined whether the response repetition effect occurred to different instances of the same characters (e.g., letter a and letter A). A remarkable repetition effect was found only for the stimulus repetition, again speaking against the categorization speedup hypothesis. They argued that the repetition effect originates in perceptual processing between percept and stimulus identification (the perceptual speedup hypothesis) or the processing from the stimulus identification all the way to the response (the response selection shortcut hypothesis). To test these possibilities, they examined what happens when the same physical stimulus is repeated on successive trials, but with different responses to be selected (i.e., odd trials require vocal responses and even trials require keypress responses). It was assumed that if the repetition effect occurs when the same

physical stimulus and the same response are repeated as suggested by the response selection shortcut hypothesis, a change in the response modality should abolish the effect; on the other hand if the repetition effect occurs only when the same stimulus is repeated as suggested by the perceptual speedup hypothesis, the effect should persist. The repetition effect was completely abolished, supporting the response selection shortcut hypothesis (Experiment 6). Furthermore, they examined whether the repetition effect transfers to the responses with the same relative spatial relations in the experiment in which keypress responses are executed with alternating hands, under the condition of the noncategorizable mapping (Experiment 7). The repetition effect was nearly eliminated. Consequently, Pashler and Baylis (1991b) concluded that the repetition effect occurs only when the same physical stimulus and the same response are repeated, that the effect is localized in the stage of response selection, and that the effect is due to bypassing of the processing of the response selection.

Campbell and Proctor (1993) argued that Pashler and Baylis (1991b) underestimated the contribution of the response repetition observed with categorizable mappings. Pashler and Baylis (1991b) rejected both the categorization speedup hypothesis and the highest link hypothesis on the basis of their failure to find the response repetition effect of equivalent magnitude to the stimulus repetition effect. As a matter of fact, however, in some of their experiments, there was a small benefit for the response repetition compared with the nonrepetition only when categorizable mappings were used. Campbell and Proctor (1993) argued that this might have suggested some involvement of the stimulus categorization and the highest link in producing the response repetition effect. To confirm these possibilities, they replicated Pashler and Baylis's (1991b) Experiment 1 and 2. They found a remarkable stimulus repetition effect for both the categorizable mapping and the noncategorizable mapping. A small but a significant response repetition effect was found, but only when categorizable mappings were used. These results were consistent with those of Pashler and Baylis (1991b). Campbell and Proctor (1993) also conducted experiments in which responses

changed on alternating trials under the conditions of categorizable mappings. In one experiment, they had subjects perform the task with their hands placed orthogonal to each other, and the stimulus categories mapped to different fingers of the hands (e.g., on odd trials, keypress responses were with the index finger of the horizontal left hand, and on even trials, keypress responses were with the middle finger of the vertical hand). Thus, alternating responses shared neither relative spatial location nor effector. Under these conditions, the stimulus and response repetition effects vanished completely. This result argued against the categorization speedup hypothesis that the repetition effect occurs to categorized stimuli, regardless of whether the repeated responses were the same or not. In another experiment, they had subjects perform the task with their hands placed horizontal to each other, and the stimulus categories mapped to the same fingers of the hands (e.g., on odd trials, keypress responses were with the index finger of the horizontal left hand, and on even trials, keypress responses with the index finger of the horizontal hand). Thus, alternating responses were similar with respect to relative spatial location and effector. The effect of the stimulus repetition was decisive. However, a small but a significant response repetition effect was found. This result was consistent with the prediction of the highest link hypothesis that the response repetition effect occurs to stimuli belonging to the same category and responses sharing the same relative spatial location and effector. Consequently, Campbell and Proctor (1993) concluded that the repetition effect is localized in the stage of response selection, as well as Pashler and Baylis's (1991b) did. They also argued that the repetition effect is predominantly due to bypassing of the processing of the response selection, but is partly due to a speedup of the selection of a response category only when the mapping of stimuli to responses is categorizable. As shown by the previous studies and as Campbell and Proctor (1993) acknowledged, however, the size of the response repetition effect (as suggested by the highest link hypothesis) was far too small to explain a substantial repetition effect. There are some reports that the response repetition effect is easier observed later in practice than early in practice (Pashler and Baylis, 1991a; Rabbitt,

1968). This might suggest that the amount of practice is a key factor that determines the contribution of the highest link to producing the repetition effect.

However, this is not the whole of the story.

#### Another Possible Locus of Repetition Effects: Response Programming Stage

Pashler and Baylis's (1991b) and Campbell and Proctor's (1993) studies consistently rejected the response execution hypothesis that the repetition effect is located in the stage of the execution of motor response. Since, as did Smith (1968), they also regarded the process of the response execution as the peripheral one, they concluded that the repetition effect is central not peripheral, in origin.

There is, however, another central process associated with the preparation of response, which occurs after response selection and precedes the execution of motor response. This process is commonly referred to as *response programming* (e.g., Klapp, 1995; Marteniuk & MacKenzie, 1980; Schmidt & Lee, 1999). Response programming is defined as more detailed specification of the response code that was established during response selection (e.g., Keele, 1986; Klapp, 1996; Rosenbaum, 1991; Sanders, 1998; Schmidt & Lee, 1999). The specification concerns kinematic or kinetic parameters such as speed and duration of movement, and its resultant representation is referred to as the *motor program* (e.g., Henry, 1980; Keele, 1968; Zelaznik & Hahn, 1985). The motor program is an abstract representation and does not contain the instructions to specific muscles.

Although the terms *selection* and *programming* are sometimes used as if they are equivalent, they can be distinguished in terms of the type of RT paradigm used to study them. In the study of response selection, the independent variable involves response uncertainty or stimulus-response compatibility, or both. These can be manipulated by varying the number of alternatives responses (e.g., Hick, 1952; Hyman, 1953) or by varying the extent of the simplicity of the mapping of stimuli to responses

(e.g., Fitts & Deininger, 1954; Fitts & Seeger, 1953). By contrast, the experimental approach common in research on response programming is to vary the parameters (e.g., movement direction, movement duration) that define a movement and then observe the consequences of these manipulations on RT. When perceptual and nonmotoric selection processes are held constant, differences in RT are thought to reflect the complexity of the programs for the different responses; more complicated movements require more elaborate motor programs, which in turn take longer to prepare.

Henry and Rogers (1960) were among the first to provide evidence for motor programming using this logic. They had the subjects make three different tasks that varied in the complexity of the movement while keeping the stimulus and response alternatives and stimulus-response mapping constant. The first task was to merely release a response key as quickly as possible after a starting signal. The second task was first to release the key to the starting signal as quickly as possible and then to grasp a ball hanging from a string. In the third task, the first two movements were the same as for the second task, but a third movement (striking the second ball) was added. It should be noted here that the stimulus and response alternatives and stimulus-response mapping were held constant so that the processing time in the stimulus-identification and response-selection stages should be the same; the only variation was in the nature of the movement. Henry and Rogers (1960) found the RT to release the key after the starting signal increased as the complexity of the movement increased. They argued that the increased RT was due to an increased amount of time required to program the movement in the response-programming stage.

Following the seminal work of Henry and Rogers (1960), their view of the motor program has been widely supported in many studies in which the response complexity was manipulated by varying number of sequence elements (Canic & Franks, 1989; Chamberlin & Magill, 1989; Christina & Rose, 1985; Christina, Fischman, Lambert, & Moore, 1985; Christina, Fischman, Verduyssen, & Anson, 1982; Fischman, 1984; Garcia-Colera & Semjen, 1987; Norrie, 1974; Sternberg, Monsell, Knoll, &

Wright, 1978), movement duration (Klapp, 1975; Klapp & Erwin, 1976; Klapp & Rodriguez, 1982; Quinn, Schmidt, Zelaznik, Hawkins, & McFarquhar, 1980), movement extent (Quinn, et al., 1980), movement direction (Fitts & Peterson, 1964), duration of force (Baba & Marteniuk, 1983; Ivry, 1986; Siegel, 1988), movement accuracy (Glencloss, 1973; Klapp, 1975; Quinn et al., 1980), sequential hand posture (Harrington, & Haaland, 1987), or similarity of sequence elements (Garcia-Colera & Semjen, 1988; Ito, 1997; Klapp & Wyatt, 1976; Semjen & Garcia-Colera, 1986).

It has been pointed out that simple RT should not necessarily depend on the response complexity to follow because subjects, knowing the required response before the starting signal is presented, might carry out programming in advance of the simple-RT interval (e.g., Anson, 1982; Klapp, 1980). However, simple RT has been found to be sensitive to the effect of response complexity in the aforementioned studies. These findings suggest that some programming is delayed until after the signal to respond, even though subjects know the required response before the signal is presented. Two possible reasons for this delay have been offered. First, constructing a motor program might automatically lead to response execution. If the programming process took place before the signal, subjects would respond erroneously on catch trials. To avoid this, programming must wait the signal (Sternberg, Monsell, Knoll, & Wright, 1978). The second reason is that a constructed motor program stored in a motor output buffer might be subject to rapid decay, in which case the motor program would have to be set up immediately before use (e.g., Canic & Franks, 1989; Ito, 1991; Sternberg et al., 1978; Verwey, 1994).

Alternative models of motor programming have been proposed to account for the response programming process. These models assume that an abstract representation of the movement sequence (i.e., motor program) is retrieved from long-term memory and is then temporarily stored as a subprogram in a short-term motor output buffer just before execution. One model explains the response-complexity effect in terms of the difference in the time needed to read the motor program from long-term memory into a

short-term motor-output buffer (Klapp, 1976). A second model attributes the effect to the difference in the time needed to edit the program while it is in the buffer (Rosenbaum, Hindorff, & Munro, 1987; Rosenbaum, Inhoff, & Gordon, 1984). A third model attributes the response-complexity effect to the difference in the time required to search the buffer for the subprogram that controls the first element of the movement (Sternberg et al., 1978). In general, the first model explains well the response-complexity effect in the task using well-learned movements. The second model accounts well for the effect in the task using the choice-RT paradigm and longer movement sequence. The third model explains well the effect in the task using the simple RT paradigm.

All these models hold the common view that the motor program is an abstract representation in the sense that the motor command can be executed by any appropriate groups of muscles, and does not contain the instructions to specific muscles involved in movement execution. For example, Klapp (1977) found that subjects benefited in the RT from advance information about the duration of a forthcoming response even if they did not know which muscles would be used to perform it. Heuer (1982) showed that choosing between right- and left-hand movements is quicker if the movements have the same spatial form than if they have different spatial forms. These findings lend strong support for the abstract concept of the motor program.

Despite a great deal of evidence for the existence of response programming and motor program, little has been known about whether the repetition effect is related to response-programming process. This reason may have been due to the fact that just as most sport psychologists who studied the process of motor preparation did not take an interest in the repetition effect, most cognitive psychologists who studied the repetition effect did not take an interest in the process of motor preparation. The present doctoral research was therefore conducted to examine the possibility that the repetition effect occurs at the stage of response programming. In the next chapter, four experiments conducted to test this hypothesis will be described.

## CHAPTER 3

### REPETITION EFFECT AT STAGE OF RESPONSE PROGRAMMING

As mentioned in Chapter 2, recent studies on the repetition effect have been consistently shown that the effect is localized in the stage of response selection and is mainly due to bypassing of the processing of the response selection (Campbell & Proctor, 1993; Pashler & Baylis, 1991b). It seems that this conclusion leaves no room for doubt. However, in spite of the abundant evidence for response programming, any studies have not been conducted to test the hypothesis that the repetition effect occurs at the stage of response programming. In the present chapter, the relation of the repetition effect and the response programming is examined by conducting four experiments. One way to test this hypothesis is to examine what happens on the RT when the similarity of serial responses is manipulated. The term *similarity* is used here to refer to the degree to which serial responses resemble each other in their force-time patterns (kinetic patterns), or more specifically, repeated responses resemble in their motor programs. In the present study, the similarity of serial responses was manipulated by requiring subjects to produce a sequence that was comprised of the same or different responses in their force-time patterns. One possible prediction is that repeating the same response may lead to a speedup or bypassing of the response programming because the motor program for the preceding response could be reused for the next response. If this account is correct, then the repetition effect should be found for all the conditions of the stimulus repetition, the response repetition and nonrepetition, regardless of whether the stimuli used were categorizable or noncategorizable. The reason the repetition effect would be found even in the nonrepetition can be explained by the fact that the motor program can apply to the

movements by any appropriate group of muscles (e.g., Heuer, 1982; Klapp, 1977). When different responses are repeated, on the other hand, no benefit should arise from response programming because the motor program for the preceding response could be not reused for the next response. Thus, the same results as those obtained by Pashler and Baylis (1991b) and Campbell and Proctor (1993) would be expected.

The experimental procedure used here was basically identical to that used by Pashler and Baylis (1991b), in that it used an information-reduction procedure with multiple stimuli mapped to each of multiple responses. However, there were two exceptions. First, as mentioned above, the similarity of serial responses were manipulated. Second, not only a choice RT paradigm but also a simple RT paradigm was adopted. During simple RT, response selection is not needed because subjects know the required response before the starting signal is presented. Thus, if the repetition effect were found in a simple RT paradigm, then the effect should reflect the contribution of the response programming rather than that of the response selection. However, no researchers have been trying to examine the repetition effect in the simple RT paradigm. Third, unlike Pashler and Baylis's procedure, serial responses were comprised of the two of the first and second responses. In this case, the repetition effect should be expected for the second response, but not for the first response. This is because there is no preceding response for the first response. Since Pashler and Baylis (1991b) believed that no repetition effect should be found for the nonrepetition condition, they merely assessed the repetition effect by comparing both the stimulus repetition and the response repetition with the norepetition, on the basis of the RT data from fifty serial responses. However, if the repetition effect were found even for the nonrepetition condition, their procedure would make it impossible to observe a beneficial effect, if any, for the nonrepetition condition. Thus, in the present experiments the repetition effect was evaluated not only by comparing differences in the RT among the three repetition conditions but also by comparing differences in the RT between the first and the second responses.

All serial responses used in this study were rapid force-production response. They were performed isometrically by squeezing a handle with a strain gauge. Subjects were required to react and produce a designated peak force by squeezing the handle as quickly and accurately as possible after the presentation of a reaction signal. The designated peak force was 30 or 50% of the maximum of isometric grip strength of each subject. Recent studies on response programming have focused on the kinetic parameters such as magnitude and duration of isometric force rather than the kinematic parameters because kinematic variation is predominantly a function of the preceding kinetic variation (Marteniuk & MacKenzie, 1980). Moreover, as suggested by Ivry (1986), the isometric force-production response seems suited to the investigation of programming for serial responses since isometric contractions are relatively invariant movements, and thus are not confounded with extent or direction of movement. Various force-time parameters associated with each force production were recorded to assess whether subjects were able to meet the task constraints imposed by the experiments.

Experiment 1 examined whether varying force magnitude influences the RTs in both simple and choice RT paradigms. Experiment 2 examined the effect of the similarity of serial responses on repetitions with a noncategorizable mapping in a choice RT paradigm. Experiment 3 examined the effect of the similarity of serial responses on repetitions with a categorizable mapping in a choice RT paradigm. Finally, Experiment 4 examined the effect of the similarity of serial responses on repetitions with a noncategorizable mapping in a simple RT paradigm.

### Experiment 1

In Experiment 2 to 4, subjects are required to perform a serial force response of 30 or 50% of the maximum of isometric grip strength of each subject. If varying magnitude of force influences the RT required to initiate the response, however, the repetition effect is confounded with the effect of force magnitude. Therefore,

Experiment 1 was conducted to examine whether varying the magnitude of force required to perform an isometric response influences simple or choice RT, or more specifically, whether programming a desired force requires a constant amount of time or not. In addition, since Experiment 2 to 3 also examines the repetition effect under the condition in which subjects are permitted to exert force freely, another purpose of the first experiment was to compare RT for experimenter-selected magnitude of force (constrained condition) with those for subject-selected magnitudes (unconstrained condition).

For this purpose, the RT is fractionated into two separate components using an electromyography (EMG) technique. The EMG is a recording of the electrical activity from muscles associated with the response and indicates the time at which the muscle shows increased activity after the reaction stimulus occurred. The first component of RT, which is called the *premotor time*, is the time between the onset of the stimulus and the first sign of heightened EMG activity. It represents the time needed to centrally process the information from the environment. The other component of RT, which is called the *motor time*, is the time between EMG onset and actual response initiation. It represents mechanical delays in the muscle's elastic component and the spread of electrical activity across the muscle. As indicated by Botwinick and Thompson (1966), Fischman (1984), Schmidt and Stull (1970), and Weiss (1965), premotor time allows a detailed analysis and assessment of central factors influencing total RT.

### *Method*

*Subjects.* Twenty graduate and undergraduate students (10 women and 10 men), ranging in age from 20 to 36 years, with a mean of 24.6 yr., volunteered to serve as subjects. They all wrote with their right hands. None had prior knowledge of the hypotheses being tested.

*Apparatus.* The apparatus was an electrohandgrip dynamometer (Takei 86004), the immovable handle of which was bolted perpendicularly to a plate on a testing table and interfaced with an NEC 9801 computer. The strain gauge attached to the handle sent a pressure-dependent electrical signal to an amplifier, which then relayed the signal on to an analogue-to-digital (A to D) converter located in the computer. The computer produced a warning tone of 300-msec. duration, controlled the foreperiod, and recorded RT data and a number of other measures from force-time curves. A visual stimulus generator (Takei 95128) with a light-emitting diode of 8 cm in diameter was placed 80 cm in front of the subject and 20 cm above the plane of the table. The generator produced either a red or a green stimulus of 100-msec. duration. The rise time of the stimulus was below 1 msec. In the simple RT condition, the red stimulus served as a signal to respond, whereas in the choice RT condition, both stimuli served as signal to respond. Durations of the warning and reaction signals were also controlled through the computer. After the completion of each response, three vertical lines and a cursor appeared on a computer screen and stayed on for 3 sec. These lines provided subjects with information about the experimenter-selected target force and the cursor provided subjects with information about the subject-generated peak force. A set of three surface electrodes of 1 cm in diameter (NEC Sanei 45073A) was used to record the EMG activity from the flexor carpi radialis of the right hand. These outputs were recorded on a Recti-Horiz (NEC Sanei 8K-20). Paper speed was set at 10 cm per second.

*Design.* The design of the experiment was a 2 x 4 (RT condition x magnitude of force) factorial with repeated measures on the last factor. The first factor had two levels of simple and choice RT conditions. The second factor had four force conditions. Ten subjects of 5 women and 5 men were randomly assigned to each of the simple and choice RT conditions.

*Procedure.* Subjects sat at the table facing the response apparatus in a quiet and dimly lit room. The subject's right forearm rested on the plate so the palmar surface of the right hand contacted the handle comfortably. The handle of the dynamometer was adjustable to the varying size grips of the subjects.

Subjects were required to react and produce a designated peak force by squeezing the handle with the preferred hand as quickly and accurately as possible after the presentation of a reaction signal. The target forces were 30, 50, and 70% of the maximum of isometric grip strength of each subject. In addition, there was an unconstrained condition in which subjects were permitted to exert force freely. In the choice RT condition, a two-choice paradigm was used. Three combinations of the four target forces were designated as 30%-50% and 70%-unconstrained, 30%-unconstrained and 50%-70%, and 30%-70%, and 50%-unconstrained. Subjects were randomly assigned to one of the three combinations. The order of the presentation of the four force conditions within each combination was also randomly determined for each subject.

Each trial began with a warning tone, followed by the reaction signal. The reaction signal occurred with a random foreperiod of either 700, 1,000, 1,300 or 1,600 msec. For the simple RT condition, catch trials were included at a rate of one-fifth of the trials to discourage subjects from anticipating the reaction signals. When a catch trial occurred, the warning tone was not followed by a reaction signal. In the simple RT condition, reactions were always produced to the red stimulus. In the choice RT condition, for half of the subjects the smaller peak force and unconstrained response were paired with the red stimulus, whereas for the other half the smaller peak force and unconstrained response were paired with the green stimulus. Subjects were given a card depicting the relation of stimuli and target forces. To help subjects produce a designated force a vertical line that indicates a target force and a cursor that indicates subject-generated force were displayed on the computer screen after each trial. In the choice RT condition, subjects were instructed to ensure that the response produced was that

specified by the stimulus. If the subjects inadvertently produced the wrong response, they were asked to notify the experimenter.

In the simple RT condition, subjects performed 50 blocked trials (30 practice trials and 20 test trials) for each force condition. The conditions were randomly ordered for each subject. The intertrial interval was 10 sec. A 1-hr. break was given after the completion of the first two conditions. In the choice RT condition, subjects performed 100 blocked trials (30 practice trials and 20 test trials for each force condition) for each of the two two-choice conditions. The order of the presentation of the two force conditions within each two-choice condition was randomly determined for each subject. The intertrial interval was 10 sec. A 1-hr. break was given after the completion of the first two-choice conditions.

All test trials on which errors (catch trial error in the simple RT condition and selection of the wrong response in the choice RT condition) occurred were repeated at the end of the condition in which they occurred.

*Dependent measures.* The dependent measures were RT, premotor time, motor time, and three force-time parameters associated with each force response (actual peak force, time to peak force, and force duration). RT was the time between the onset of the reaction signal and the initiation of force production. Initiation of force production was defined as the point in time at which the value from the dynamometer rose above 0.7 kg. This value was just above the noise threshold. Premotor time was calculated later by subtracting motor time from reaction time. The actual peak force was expressed as a percentage of the maximum force of each subject.

These data were analysed via a two-way analysis of variance (ANOVA), with the RT condition as a between-subjects factor and the force magnitude as a within-subjects factor. All post hoc analyses were performed using Newma-Keuls test at the .05 level.

## Results

*Force-time measures.* The results of force-time measures were very similar. ANOVAs showed significant interactions between the two factors ( $F(3, 54) = 5.23$  for actual peak force,  $F(3, 54) = 7.43$  for time to peak force, and  $F(3, 54) = 7.94$  for force duration,  $ps < .01$ ). Not surprisingly, these interactions were predominantly due to high variability of the responses in the unconstrained conditions. However, systematic results were observed for the constrained conditions. A Newman-Keuls test revealed that actual peak force significantly increased with increases in target force for both RT conditions, which did not differ from each other. Also, time to peak force and force duration significantly increased with increases in actual peak force in both RT conditions, which did not differ. Means of actual peak force were 32, 51, and 68% for the 30, 50, and 70% conditions, respectively. As is evident in these data, the subjects' mean actual peak force for each target force closely matched the target forces for both RT conditions. Means of time to peak force were 106, 137, and 167 msec. for the 30, 50 and 70% conditions, respectively. Means of force duration were 235, 287 and 336 msec. for the 30, 50, and 70% conditions, respectively. These results indicate that more time was needed to make stronger isometric contractions. However, all of the responses were quite rapid, as is indicated by the overall mean time to peak force of 137 msec. Therefore, it can be considered that the force-production task was performed in a ballistic fashion. These findings indicate that subjects were able to meet the task constraints imposed by the experiment. Means of maximal isometric grip strength were 48.9 and 49.2 kg for the simple and choice RT groups, respectively, which was not significantly different from each other.

*RT and premotor time.* Figure 2 shows mean premotor time as a function of magnitude of force in both simple and choice RT conditions. The results of the RT and premotor time were very similar. ANOVAs showed that main effects for RT condition

( $F(1, 18) = 58.74$  for RT and  $F(1, 18) = 62.08$  for premotor time,  $ps < .001$ ) were significant. As was anticipated, the simple RT condition produced significantly shorter RT and premotor time than did the choice RT condition. Most important, the main effects for magnitude of force and the interactions between the two factors were not significant. These indicated that RT and premotor time did not significantly differ among the 30, 50, and 70% conditions and between the constrained and unconstrained conditions in both RT conditions.

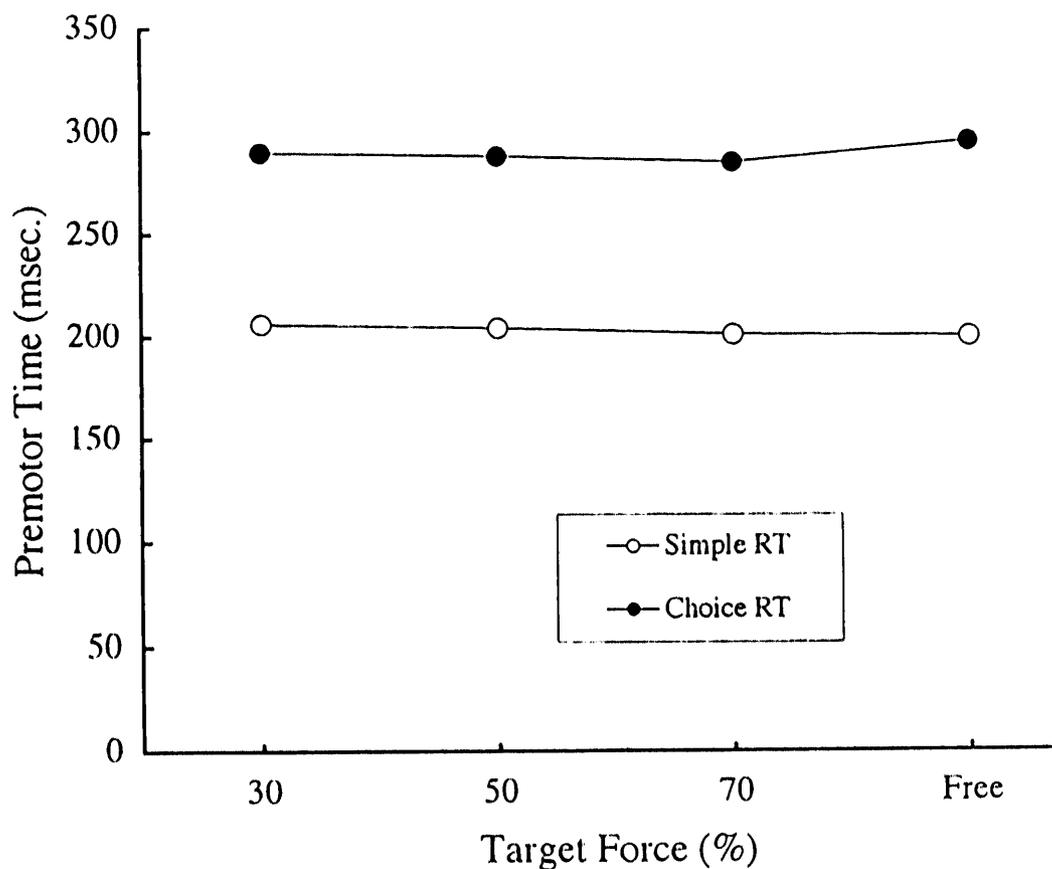


Figure 2. Mean premotor time in Experiment 1 as a function of magnitude of force in both simple and choice reaction time (RT) conditions.

*Motor time.* The main effect for force condition ( $F(3, 54) = 4.04$ ,  $p < .05$ ) as well as the interaction between the two factors ( $F(3, 54) = 2.55$ ,  $p < .05$ ) was significant.

The analysis of interaction showed that the unconstrained condition produced slightly shorter motor time than did the 50 and 70% conditions for the simple RT condition. However, motor times did not significantly differ among the 30, 50, and 70% conditions in both RT conditions, which did not differ from each other. Mean motor times were 49, 52, 52, and 47 msec. for the 30, 50, 70%, and unconstrained conditions, respectively.

*Error rates.* No catch trial errors were produced for the simple RT condition. Errors in force selection within the choice RT group were infrequent as indicated by the overall mean error rates of 3.8%, which was evenly distributed among the conditions.

### *Discussion*

Experiment 1 was conducted to examine the effects of variations in magnitude of force on the RT and premotor time in both simple and choice RT paradigms and to compare RT and premotor time for the experimenter-selected magnitude of force with those for subject-selected magnitudes. The results of force-time parameters showed that time to peak force and duration of force increased with increases in actual peak force corresponding to each target force. These results suggest that each force response contain a different kinetic pattern, thus a different motor program.

More important results were that the RT required to initiate force response did not change across the range of forces examined in both simple and choice RT conditions, regardless of whether a desired force is selected by the experimenter or by the subject. The same pattern was also evident for premotor time. Since it can be considered that premotor time is a more valid indicant of programming time than RT (e.g., Anson, 1982; Fischman, 1984; Weiss, 1965), the present findings suggest that the time required to program force response is invariant across the range of forces examined. These findings also confirm that the effect of magnitude of force is not confounded with the repetition effect examined in the following experiments.

## Experiment 2

Experiment 2 was conducted to examine the effect of the similarity of the serial response on the repetition effect with a two-choice RT task in which two stimuli were assigned to each of two force responses. The stimuli were selected to minimize any possibility that two stimuli assigned to a response could be grouped into common categories. That is, the mapping of stimuli to responses was noncategorizable. The similarity of the serial response was manipulated by making subjects repeat the same peak force response within a sequence (same force condition) or the different peak force response within a sequence (different force condition). If the repetition effect occurs at the stage of response programming, then it would be expected that in the same force condition, the choice RT to initiate the second response is shorter than that to initiate the first response for all the repetition conditions. In the different force condition, however, the shorter choice RT should be found only for the stimulus repetition as shown by Pashler and Baylis (1991b). It would be also expected that the choice RT to initiate the second response is shorter for the same force condition than for the different force condition in all the repetition conditions. In this experiment, the EMG technique was not used because Experiment 1 showed that the results of RT and premotor time were essentially parallel.

### *Method*

*Subjects.* Thirty graduate and undergraduate students (15 women and 15 men), ranging in age from 18 to 36 years, with a mean of 21.8 yr., volunteered to serve as subjects. They all wrote with their right hands. None had prior knowledge of the hypotheses being tested.

*Apparatus.* The apparatus was almost the same as in Experiment 1 except that an auditory stimulus generator (Takei 332) was used to present two tones of a low-pitch tone of 500 Hz and a high-pitch tone of 2,000 Hz. The rise time of the stimulus was below 5 msec.

*Design.* The design of the experiment was a 3 x 3 x 2 (serial pattern x repetition condition x serial position) factorial with repeated measures on the last two factors. The first factor had three levels of the same force, different force, and free force conditions. The second factor had three levels of the stimulus repetition, response repetition, and nonrepetition conditions. The third factor had two levels of the first and second responses. Ten subjects of 5 women and 5 men were randomly assigned to each of the same force, different force, and free force conditions.

*Procedure.* Stimuli as reaction signals were the visual stimuli of a red light and a green light, and the auditory stimuli of a low-pitch tone of 500 Hz and a high-pitch tone of 2,000 Hz. For half of the subjects the red light and low tone were assigned to the response handle of the right hand and the green light and high tone were assigned to the response handle of the left hand; this assignment was reversed for the remaining subjects. Subjects were given a card depicting the mapping of stimuli to responses. Stimuli were randomly presented with the constraint that presentation of each stimulus occurred equally, so that the numbers of trials in each repetition condition varied. That is, the expected proportion of stimulus repetitions was equal to 1/4, the expected proportion of response repetitions was equal to 1/4, and the expected proportion of nonrepetitions was equal to 1/2.

Each trial began with a warning signal of 300-msec. duration, followed by one of the four stimuli of 100-msec. duration with a fixed foreperiod of 1,000 msec. This stimulus served as the signal for the subjects to initiate the first response. Following a 1,000-msec. interval after the completion of the first response, one of the four stimuli of

100-msec. duration was presented, which was the signal to initiate the second response. Thus, like Pashler and Baylis's (1991b) and Campbell and Proctor's (1993) experiments, the response-stimulus interval was 1,000 msec. The task was to react and produce the sequence of same or different peak force by squeezing a handle as quickly and accurately as possible after each signal. In the same force condition, the sequence was comprised of 30%-30% of the maximum of the isometric grip strength of each subject. The subjects were instructed to reproduce the same force as in the first response, whether or not they felt that the peak force produced in the first response deviated from the required force. In the different force condition, on the other hand, the sequence was comprised of 50%-30% of the maximum of the isometric grip strength of each subject. In the free force condition, subjects were permitted to respond by exerting force freely. To help subjects produce appropriate peak forces two vertical lines which indicate target peak force and a cursor which indicates subject-generated peak force were displayed on the computer screen for 3 sec. after each trial.

Subjects participated in two consecutive daily sessions. In the first session, subjects performed 288 practice trials for each of the same force and different force conditions, and 72 practice trials for the free force condition. In the second session, subjects performed 288 trials (144 practice trials and 144 test trials) for each of the same force and different force conditions and 144 trials (72 practice trials and 72 test trials) for the free force condition. The intertrial interval was 10 sec. A 3-min. break was given every 48 trials. All test trials on which response selection errors occurred were considered as error trials and were omitted from analysis. The other procedure was the same as in Experiment 1.

*Dependent measures.* The dependent measures were choice RT and three force-time measures associated with each force response (actual peak force, time to peak force, and impulse). Choice RT was the time between the onset of the reaction signal and the initiation of force production. Initiation of the response was defined as

the point in time at which the value from the dynamometer rose above 0.7 kg. The end of the response was defined as the time at which the value from dynamometer fell below 0.3 kg. The actual peak force was expressed as a percentage of the maximum force of each subject.

Unless noted otherwise, these data were analyzed via a three-way ANOVA, with the serial pattern (same force or different force) as a between-subjects factor, repetition condition (stimulus repetition, response repetition, or nonrepetition), and serial position (first or second response) as within-subjects factors. Because the numbers of trials for the free force condition was different from those for the other conditions, the data of the free force condition were analyzed via a two-way repeated-measure ANOVA with repetition condition and serial position. All post hoc analyses were performed using the least significant difference (LSD) test at the .05 level.

### *Results*

*Force-time measures.* The results of force-time measures were very similar. The interactions between serial pattern and serial position were significant ( $F(1, 18) = 206.55$  for actual peak force,  $F(1, 18) = 76.20$  for time to peak force, and  $F(1, 18) = 77.72$  for impulse,  $ps < .001$ ). As was anticipated, the analyses of interactions indicated that with the same force condition, the first response was not significantly different from the second response for all the force-time measures. With the different force condition, however, the first response was significantly different from the second response for all the force-time measures ( $F(1, 18) = 359.07$  for actual peak force,  $F(1, 18) = 142.51$  for time to peak force, and  $F(1, 18) = 138.77$  for impulse,  $ps < .001$ ). With the same force condition, means of actual peak force were 29 and 31%; means of time to peak force were 94 and 96 msec.; means of impulse were 1.4 and 1.5 kg · s, for the first and second responses, respectively. Also with the different force condition, means of actual peak force were 52 and 29%; means of time to peak force were 136 and 108 msec.; means of

impulse were 3.2 and 1.7 kg · s, for the first and second responses, respectively. As is evident in these data, the subjects' mean actual peak force closely matched the target force of 30 or 50%. Moreover, all of the responses were quite rapid as is indicated by the overall mean time to peak force of 109 msec. Therefore it can be considered that the force-production task was performed in a ballistic fashion. These findings indicate that subjects were able to meet the task constraints imposed by the experimenter. With the free force condition, interactions between the two factors were significant for all the force-time measures ( $F(2, 18) = 8.30$  for actual peak force,  $F(2, 18) = 9.64$  for time to peak force,  $F(2, 18) = 15.48$  for impulse,  $ps < .01$ ), indicating that the force-time patterns were different among the conditions. In addition, the data of maximal isometric grip strength were analyzed via a two-way ANOVA, with the serial pattern (same force, different force, or free force) as a between-subjects factor and hand (right or left) as a within-subjects factor. Only a main effect for hand was significant ( $F(1, 27) = 31.18$ ,  $p < .01$ ), indicating that the right hands (43.5 kg) produced larger forces than did the left hands (40.9 kg).

*Choice RT.* Figure 3 shows mean choice RT as a function of repetition condition and serial position for each serial pattern. Because the choice RT to initiate the first response differed remarkably between the same force and different force conditions, separate two-way repeated-measure ANOVAs with repetition condition and serial position were carried out with both the same force and different force conditions. The comparison of the choice RTs to initiate the second responses between the same force and different force conditions was made via a one-way analysis of covariance.

With the same force condition, the interaction between repetition condition and serial position was significant ( $F(2, 18) = 27.86$ ,  $p < .001$ ). The analysis of interaction indicated that there were significant differences in RTs among the repetition conditions for the second response ( $F(2, 18) = 35.10$ ,  $p < .001$ ). An LSD test revealed that stimulus repetition RT was significantly shorter than response repetition RT and nonrepetition

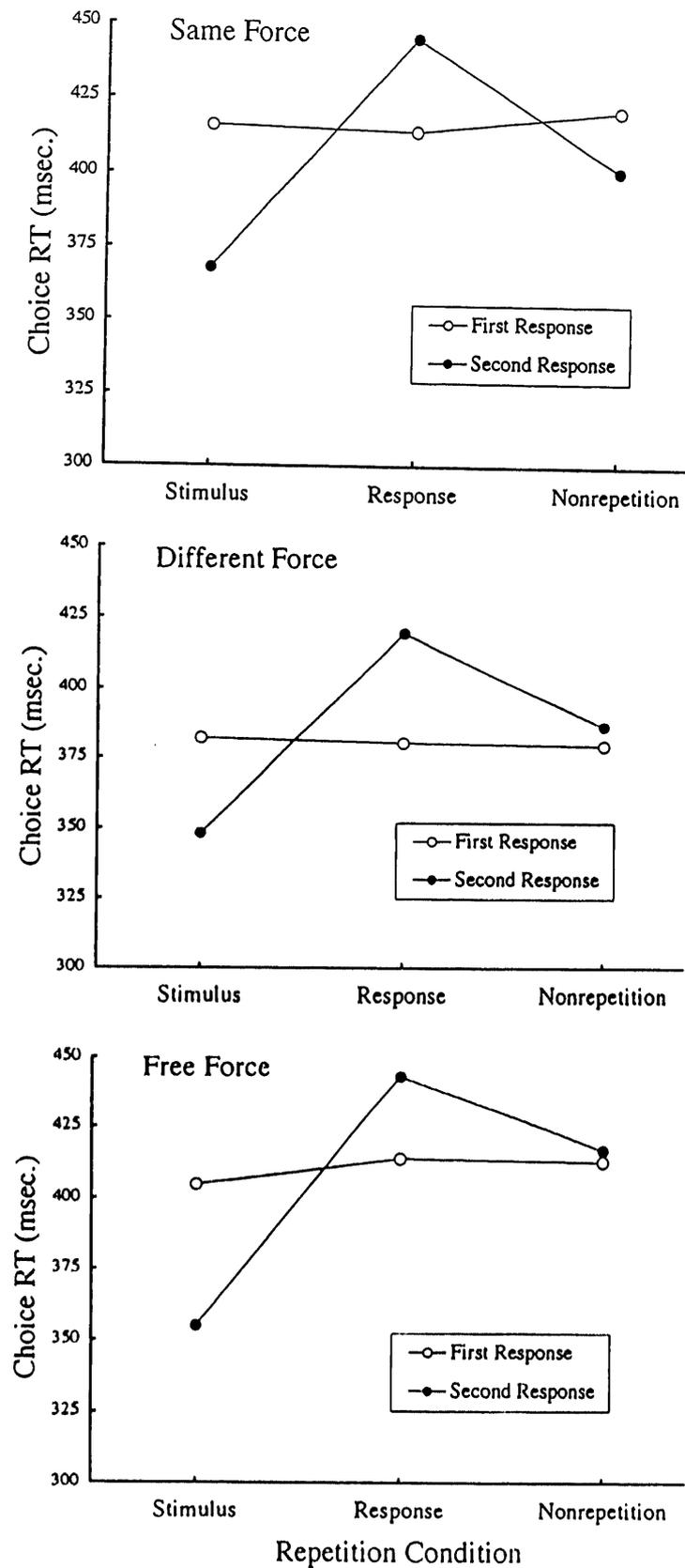


Figure 3. Mean choice reaction time (RT) in Experiment 2 as a function of repetition condition, serial position, and serial pattern for a noncategorizable mapping.

RT and that nonrepetition RT was significantly shorter than response repetition RT. Most important, stimulus repetition RT ( $F(1, 9) = 31.48, p < .001$ ) and nonrepetition RT ( $F(1, 9) = 8.39, p < .05$ ) were significantly shorter for the second response than for the first response. Moreover, response repetition RT was significantly longer for the second response than for the first response ( $F(1, 9) = 9.79, p < .05$ ). These results indicate that the repetition effects were found for the stimulus repetition and nonrepetition.

Also with the different force condition, the interaction between repetition condition and serial position was significant ( $F(2, 18) = 39.49, p < .001$ ). The analysis of interaction indicated that there were significant differences in RTs among the repetition conditions for the second response ( $F(2, 18) = 35.10, p < .001$ ). An LSD test revealed that stimulus repetition RT was significantly shorter than response repetition RT and nonrepetition RT and that nonrepetition RT was significantly shorter than response repetition RT. Most important, stimulus repetition RT ( $F(1, 9) = 13.21, p < .01$ ) was significantly shorter for the second response than for the first response, and that response repetition RT ( $F(1, 9) = 9.85, p < .05$ ) was significantly longer for the second response than for the first response. Nonrepetition RT did not differ between the first and second responses. These results indicate that the repetition effect was found only for the stimulus repetition. The analyses of covariance revealed that RTs to initiate the second responses were shorter for the same force condition than for the different force condition in the stimulus repetition ( $F(1, 17) = 3.53, .05 < p < .10$ ) and nonrepetition ( $F(1, 17) = 5.08, p < .05$ ).

The result of RT with the free force condition was very similar to that with the different force condition. The interaction between repetition condition and serial position was significant ( $F(2, 18) = 26.67, p < .001$ ). The analysis of interaction indicated that there were significant differences in RTs among the repetition conditions for the second response ( $F(2, 18) = 41.41, p < .001$ ). An LSD test revealed that stimulus repetition RT was significantly shorter than response repetition RT and nonrepetition RT and that nonrepetition RT was significantly shorter than response repetition RT. Most

important, stimulus repetition RT ( $F(1, 9) = 35.29, p < .001$ ) was significantly shorter for the second response than for the first response, and that response repetition RT ( $F(1, 9) = 13.59, p < .01$ ) was significantly longer for the second response than for the first response. Nonrepetition RT did not differ between the first and second responses. As with the different force condition, these results indicate that the repetition effect was found only for the stimulus repetition.

*Error rates.* The interaction between repetition condition and serial position was significant ( $F(2, 36) = 8.89, p < .01$ ). The analysis of interaction indicated that the error rates during the second responses significantly differed among the repetition conditions ( $F(2, 36) = 18.12, p < .01$ ). An LSD test revealed that the response repetition (7.2%) produced significantly higher error rate than did both the stimulus repetition (1.4%) and nonrepetition (1.8%), which were not significantly different from each other.

### *Discussion*

The results of force-time parameters showed that subjects were able to meet the task constraints imposed by the experimenter. Thus, it can be supposed that serial responses were executed with the same motor program in the same force condition, whereas serial responses were executed with the different motor program in the different force condition.

The pattern of results on choice RT found for the different force and free force conditions was completely consistent with the results observed by Campbell and Proctor's (1993) and Pashler and Baylis's (1991b) experiments in which the mapping of stimuli to responses was noncategorizable. The repetition effect was observed only for the stimulus repetition. Based on the logic mentioned in Chapter 2, this finding supports the response selection shortcut hypothesis proposed by Pashler and Baylis (1991b). Also with the same force condition, a remarkable repetition effect was observed for the

stimulus repetition. However, the most important finding was that the repetition effect was also found for the nonrepetition. It should be noted here that for both the same force and different force conditions, the stimulus and response alternatives and the stimulus-response mapping were held constant, so that the processing speed in the perceptual-identification and response-selection stages should also be the same. The only variation was in the nature of the response. If the repetition effect occurs only at the stage of response selection, then RT for the nonrepetition should have been the same between both conditions, regardless of the nature of the response. The data did not support this prediction. Therefore, this result is consistent with the present hypothesis that the repetition effect occurs at the stage of response programming. However, the stimulus repetition effect was significantly larger for the same force condition than for the different force condition. This suggests that overall stimulus repetition effect found for the same force condition is comprised of the effects that arise from at least two different stages, one that stems from the response selection and another that stems from response programming. However, the size of the repetition effect obtained was significantly larger for the stimulus repetition than for the nonrepetition. This suggests that response selection is the primary locus of the repetition effect and response programming is the secondary locus of the effect in a serial choice reaction.

Another interesting aspect of present data was that no response repetition effect was found for both different force and free force conditions. On the contrary, the response repetition produced significantly longer RT for the second response than for the first response. This pattern was similar to the results observed by Campbell and Proctor's (1993), Pashler and Baylis's (1991b) and Smith's (1968) experiments. The same pattern was also evident for the same force condition, speaking against the response-programming hypothesis. According to the present hypothesis, repeating the same response should have produced the repetition effects for all the repetition conditions. This was not the case. This result may suggest that making the same response to a new signal immediately after having made that response to a different

signal causes some additional inhibition. In fact, the response error during the second response was most pronounced in the response repetition.

Taken together, the findings of Experiment 2 suggest that under circumstances that repeated responses are the same in terms of their force-time patterns, the repetition effect originates in the stage of not only response selection but also response programming.

### Experiment 3

Experiment 3 was basically a replication of Experiment 2 with one exception that two stimuli assigned to a response were selected so that they could be grouped into common categories. That is, the mapping of stimuli to responses was categorizable. The hypotheses tested here were also the same as in Experiment 2.

#### *Method*

*Subjects.* Thirty graduate and undergraduate students (15 women and 15 men), ranging in age from 18 to 38 years, with a mean of 23.3 yr., volunteered to serve as subjects. They all wrote with their right hands. None had prior knowledge of the hypotheses being tested. Ten subjects of 5 women and 5 men were randomly assigned to each of the same force, different force, and free force conditions.

*Apparatus.* The apparatus was the same as in Experiment 2.

*Design.* Design was the same as in Experiment 2.

*Procedure.* Unlike Experiment 2, the mapping of stimuli to responses was categorizable. For half of the subjects the red light and green light were assigned to the

response handle of the right hand and the low tone and high tone were assigned to the response handle of the left hand; this assignment was reversed for the remaining subjects. The other procedure was the same as in Experiment 2.

*Dependent measures.* Dependent measures were the same as in Experiment 2.

### *Results*

*Force-time measures.* The results of force-time measures were very similar. The interactions between serial pattern and serial position were significant ( $F(1, 18) = 125.42$  for actual peak force,  $F(1, 18) = 89.85$  for time to peak force, and  $F(1, 18) = 83.81$  for impulse,  $ps < .001$ ). The analyses of interactions indicated that with the same force condition, the first response was not significantly different from the second response for all the force-time measures. With the different force condition, however, the first response was significantly different from the second response for all the force-time measures ( $F(1, 18) = 254.81$  for actual peak force,  $F(1, 18) = 191.02$  for time to peak force, and  $F(1, 18) = 184.24$  for impulse,  $ps < .001$ ). With the same force condition, means of actual peak force were 33 and 33%; means of time to peak force were 103 and 102 msec.; means of impulse were 1.8 and 1.7 kg · s, for the first and second responses, respectively. With the different force condition, means of actual peak force were 52 and 30%; means of time to peak force were 130 and 101 msec; means of impulse were 3.3 and 1.7 kg · s, for the first and second responses, respectively. As is evident in these data, the subjects' mean actual peak force closely matched the target force of 30 or 50%. Moreover, all of the responses were quite rapid as is indicated by the overall mean time to peak force of 109 msec. Therefore it can be considered that the force-production task was performed in a ballistic fashion. These findings indicate that subjects were able to meet the task constraints imposed by the experimenter. Also with the free force

condition, interactions between the two factors were significant for all the force-time measures ( $F(2, 18) = 14.05$  for actual peak force,  $F(2, 18) = 10.27$  for time to peak force,  $F(2, 18) = 19.03$  for impulse,  $ps < .01$ ). As was anticipated, the force-time patterns were different among the conditions. In addition, the result of maximal isometric grip strength showed a significant main effect for hand ( $F(1, 27) = 34.42$ ,  $p < .01$ ), indicating that the right hands (44.3kg) produced larger forces than did the left hands (41.3 kg).

*Choice RT.* Figure 4 shows mean choice RT as a function of repetition condition and serial position for each serial pattern. Because the choice RT to initiate the first response differed remarkably between the same force and different force conditions, separate two-way repeated-measure ANOVAs with repetition condition and serial position were carried out with both the same force and different force conditions. The comparison of the choice RTs to initiate the second responses between the same force and different force conditions was made via a one-way analysis of covariance.

With the same force condition, the interaction between repetition condition and serial position was significant ( $F(2, 18) = 31.58$ ,  $p < .001$ ). The analysis of interaction indicated that there were significant differences in RTs among the repetition conditions for the second response ( $F(2, 18) = 12.61$ ,  $p < .01$ ). An LSD test revealed that stimulus repetition RT was significantly shorter than response repetition RT and nonrepetition RTs and that nonrepetition RT was significantly shorter than response repetition RT. Most important, stimulus repetition RT ( $F(1, 9) = 41.23$ ,  $p < .001$ ) and nonrepetition RT ( $F(1, 9) = 40.76$ ,  $p < .001$ ) were significantly shorter for the second response than for the first response and that response repetition RT for the first response did not differ from that for the second response. These results indicate that the repetition effects were found for the stimulus repetition and nonrepetition.

Also with the different force condition, the interaction between repetition condition and serial position was significant ( $F(2, 18) = 15.02$ ,  $p < .01$ ). The analysis of

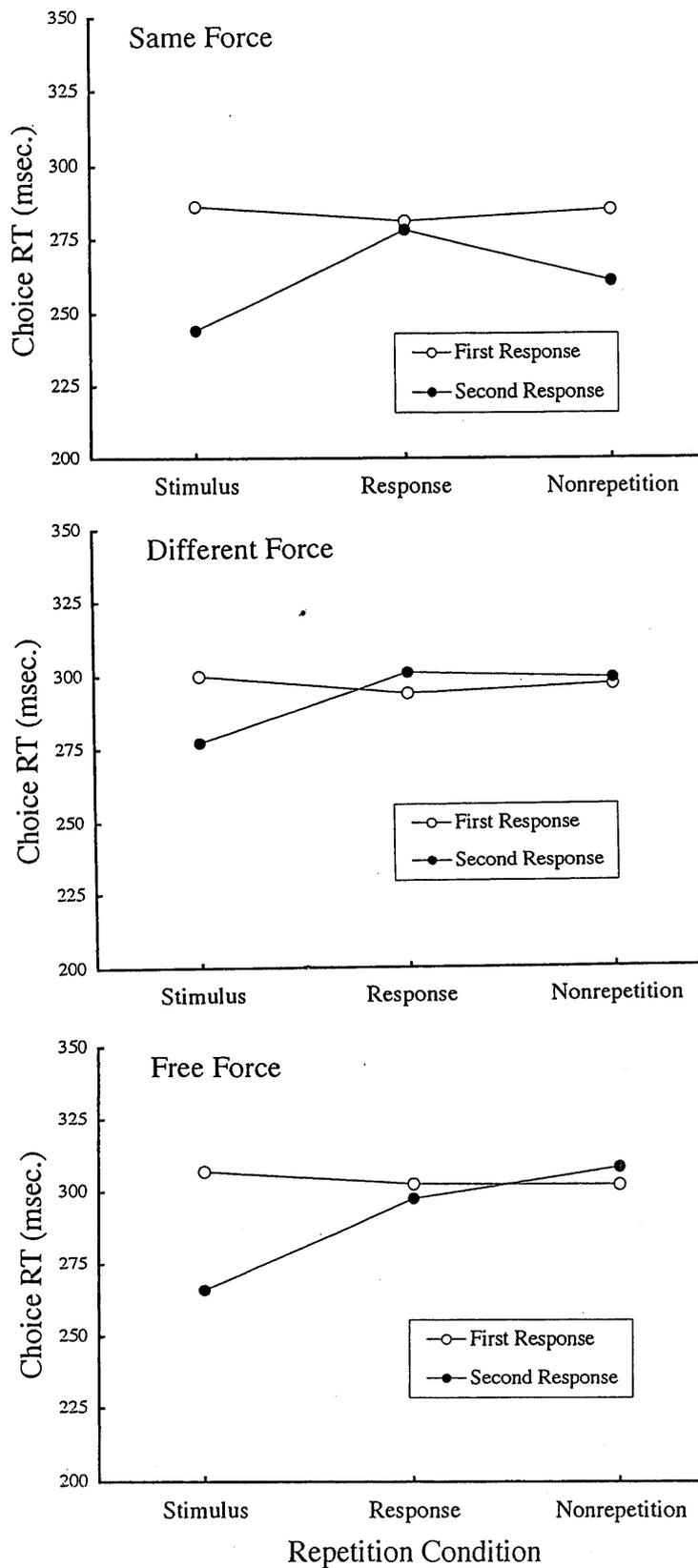


Figure 4. Mean choice reaction time (RT) in Experiment 3 as a function of repetition condition, serial position, and serial pattern for a categorizable mapping.

interaction indicated that there were significant differences in RTs among the repetition conditions for the second response ( $F(2, 18) = 13.14, p < .01$ ). An LSD test revealed that stimulus repetition RT was significantly shorter than both response repetition and nonrepetition RTs, which did not differ from each other. Most important, stimulus repetition RT ( $F(1, 9) = 36.27, p < .01$ ) was significantly shorter for the second response than for the first response, whereas both response repetition and nonrepetition RTs for the first response did not significantly differ from those for the second response. These results indicate that the repetition effect was found only for the stimulus repetition. The analyses of covariance revealed that RTs to initiate the second responses were shorter for the same force condition than for the different force condition in all of stimulus repetition ( $F(1, 17) = 11.08, p < .01$ ), response repetition ( $F(1, 17) = 3.73, .05 < p < .10$ ), and nonrepetition ( $F(1, 17) = 12.22, p < .01$ ).

The result of RT with the free force condition was very similar to that with the different force condition. The interaction between repetition condition and serial position was significant ( $F(2, 18) = 32.98, p < .001$ ) indicating that there were significant differences in RTs among the repetition conditions with the second response ( $F(2, 18) = 40.82, p < .001$ ). An LSD test revealed that stimulus repetition RT was significantly shorter than both response repetition and nonrepetition RTs, which did not differ from each other. Most important, stimulus repetition RT ( $F(1, 9) = 69.62, p < .001$ ) was significantly shorter for the second response than for the first response, whereas both response repetition and nonrepetition RTs for the first response were not significantly different from those for the second response. As with the different force condition, these results indicate that the repetition effect was found only for the stimulus repetition.

*Error rates.* The interaction between repetition condition and serial position was significant ( $F(2, 36) = 21.41, p < .001$ ). The analysis of interaction indicated that the error rates during the second responses significantly differed among the repetition

conditions ( $F(2, 36) = 32.25, p < .001$ ). An LSD test revealed that the response repetition (9.2%) produced significantly higher error rate than did both the stimulus repetition (2.1%) and nonrepetition (1.5%), which were not significantly different from each other.

### *Discussion*

Examination of the force-time parameters showed that subjects were able to meet the task constraints imposed by the experimenter.

The results on choice RT were almost consistent with those observed in Experiment 2. With the different force and free force conditions, the repetition effect was observed only for the stimulus repetition. With the same force condition, on the other hand, the repetition effect was observed for the stimulus repetition and nonrepetition, supporting the response programming hypothesis as well as the response selection hypothesis. Again, the size of the repetition effect obtained was significantly larger for the stimulus repetition than for the nonrepetition. As in Experiment 2, this suggests that response selection is the primary locus of the repetition effect and response programming is the secondary locus of the effect, regardless of whether the mapping was categorizable or noncategorizable.

In terms of the highest link hypothesis (Campbell & Proctor, 1993; Pashler & Baylis, 1991b), if the response repetition effect reflects the speedup of processing from the stimulus category to response category, then the response repetition effect should have occurred only when the mapping was categorizable. However, no response repetition effect was found for both different force and free force conditions. This result is consistent with the result observed by Pashler and Baylis's (1991b) experiment, speaking against the highest link hypothesis. Also with the same force condition, on the other hand, response repetition effect was not found. However, the fact that the RT to initiate the second response was significantly shorter for the same force condition than

for the different force condition may partly support the response-programming hypothesis.

In Experiment 2 in which the noncategorizable mapping was used, the response repetition produced significantly longer RT for the second response than for the first response. In the present experiment in which the categorizable mapping was used, however, this trend was not found. Thus, the inhibitory effect observed in Experiment 2 might have stemmed from making the same response to a new signal which could be not grouped into common categories immediately after having made that response to a signal.

In conclusion, the findings of Experiment 3 suggest that when repeated responses are the same in terms of their force-time patterns, the repetition effect occurs at the stage of not only response selection but also response programming, regardless of the nature of the mapping of the stimuli to the responses.

#### Experiment 4

Experiment 4 was basically a replication of Experiment 2 with one exception that instead of a choice RT paradigm, a simple RT paradigm was adopted. During simple RT, response selection is not needed because subjects know the required response before the starting signal is presented. Thus, if the repetition effect is found in a simple RT paradigm, then the effect should predominantly originate in the stage of the response programming, not the stage of the response selection. It was assumed that the repetition effect should be observed for the same force condition, but not for the different force condition, and that the size of the effect observed for the same force condition should be the same across all the repetition conditions. In this experiment, the free force condition was excluded because as shown in Experiment 2 and 3, the results on RT observed for the free force condition were consistent with those for the different force condition.

### *Method*

*Subjects.* Twenty graduate and undergraduate students (10 women and 10 men), ranging in age from 20 to 29 years, with a mean of 21.6 yr., volunteered to serve as subjects. They all wrote with their right hands. None had prior knowledge of the hypotheses being tested.

*Apparatus.* The apparatus was the same as in Experiment 2.

*Design.* The design of the experiment was a 2 x 3 x 2 (serial pattern x repetition condition x serial position) factorial with repeated measures on the last two factors. The first factor had two levels of the same force and different force conditions. The second factor had three levels of the stimulus repetition, response repetition, and nonrepetition conditions. The third factor had two levels of the first and second responses. Ten subjects of 5 women and 5 men were randomly assigned to each of the same force and different force condition.

*Procedure.* Unlike in Experiment 2, the simple RT paradigm was used. Subjects were informed which stimulus was presented and which response was to prepare before each trial. Catch trials were included at a rate of one-sixth of the trials for each of the first and second responses to discourage subjects from anticipating the reaction signals. When a catch trial occurred, the warning tone was not followed by a reaction signal.

Subjects participated in two consecutive daily sessions. In the first session, subjects performed 192 practice trials for each of the same force and different force conditions. In the second session, subjects performed 192 trials (96 practice trials and 96 test trials) for each of the same force and different force conditions. The intertrial interval was 10 sec. A 3-min. break was given every 64 trials. The other procedure was

the same as in Experiment 2.

*Dependent measures.* Dependent measures were the same as in Experiment 2 except that instead of choice RT simple RT was measured. These data were analyzed via a three-way ANOVA, with the serial pattern (same force or different force) as a between-subjects factor, repetition condition (stimulus repetition, response repetition, or nonrepetition), and serial position (first or second response) as within-subjects factors.

### *Results*

*Force-time measures.* The results of force-time measures were very similar. The interactions between serial pattern and serial position were significant ( $F(1, 18) = 256.94$  for actual peak force,  $F(1, 18) = 59.57$  for time to peak force, and  $F(1, 18) = 86.36$  for impulse,  $ps < .001$ ). The analyses of interactions indicated that with the same force condition, the first response was not significantly different from the second response for all the force-time measures. With the different force condition, however, the first response was significantly different from the second response for all the force-time measures ( $F(1, 18) = 441.41$  for actual peak force,  $F(1, 18) = 120.24$  for time to peak force, and  $F(1, 18) = 152.43$  for impulse,  $ps < .001$ ). With the same force condition, means of actual peak force were 31 and 33%; means of time to peak force were 105 and 106 msec.; means of impulse were 1.9 and 2.1 kg · s, for the first and second responses, respectively. Also with the different force condition, means of actual peak force were 54 and 29%; means of time to peak force were 130 and 101 msec; means of impulse were 3.3 and 1.5 kg · s, for the first and second responses, respectively. As is evident in these data, the subjects' mean actual peak force closely matched the target force of 30 or 50%. Moreover, all of the responses were quite rapid as is indicated by the overall mean time to peak force of 111 msec. Therefore it can be considered that the force-production task was performed in a ballistic fashion. These findings indicate that subjects were able to

meet the task constraints imposed by the experimenter. The result of maximal isometric grip strength showed a significant main effect for hand ( $F(1, 18) = 6.20, p < .05$ ), indicating that the right hands (45.6 kg) produced larger forces than did the left hands (43.6 kg).

*Simple RT.* Figure 5 shows mean simple RT as a function of repetition condition and serial position for each serial pattern.

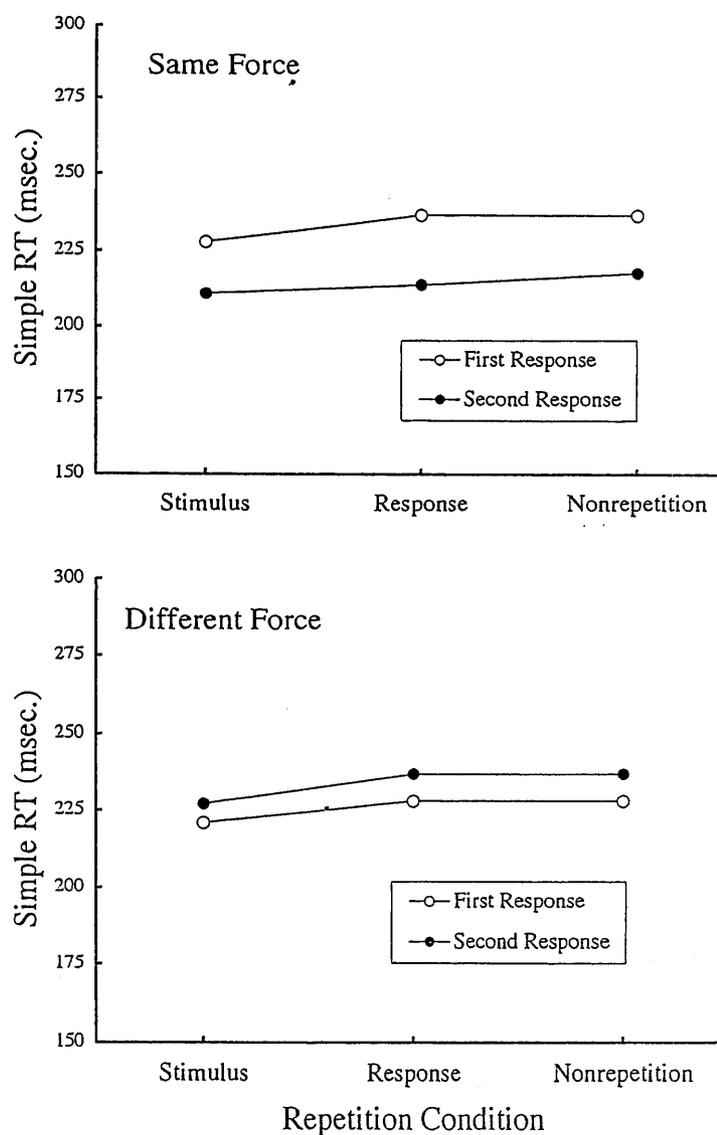


Figure 5. Mean simple reaction time (RT) in Experiment 4 as a function of repetition condition, serial position, and serial pattern.

The ANOVA showed that only the interaction between serial pattern and serial position was significant ( $F(1, 18) = 13.50, p < .01$ ). The interaction indicated that the same force condition produced significantly shorter simple RT for the second response than for the first response ( $F(1, 18) = 13.59, p < .01$ ), but the different force condition did not. These results indicate that the repetition effect was found only for the same force condition. In addition, the failure to find significant interactions between repetition condition and serial pattern and between repetition condition and serial position indicate that the size of the repetition effect observed was similar across all the repetition conditions.

*Error rates.* Catch trial errors were extremely infrequent as is indicated by the overall mean error rate of 0.3%, which was evenly distributed across all conditions.

### *Supplementary Experiment*

As hypothesized, the repetition effect was observed only for the same force condition. Moreover, the size of the effect obtained did not differ among all the repetition conditions. These findings seem to support the present view that the repetition effect seen in simple RT predominantly originates in the stage of the response programming. However, one might argue that the effect observed was simply due to decreases in time required for the electrical or physiological activity associated with muscle contraction rather than decreases in time required for response programming. Although Experiment 1 in which the EMG technique was adopted showed no difference in motor times among target forces, it did not deal with a serial reaction. Thus, this supplementary experiment was conducted to examine whether the repetition effect observed for the same force condition was due to decreases in time required for response programming or simply to decreases in time required for the electrical or physiological activity associated with muscle contraction. For this purpose, as in

Experiment 1, the EMG technique was employed to separate premotor and motor time effects.

Eight graduate and undergraduate students (4 women and 4 men), ranging in age from 20 to 23 years, with a mean of 21.5 yr., volunteered to serve as subjects. They all wrote with their right hands.

The design of the experiment was a 2 x 2 x 2 (serial pattern x target force x serial position) factorial with repeated measures on all factors. The first factor had two levels of the same force and different force conditions. The second factor had two levels of 30 and 50% target forces. The third factor had two levels of the first and second responses.

The apparatus was almost the same as in Experiment 1. Subjects were required to react and produce a designated peak force by squeezing the handle with the preferred hand as quickly and accurately as possible after each of the first and the second reaction signals. Unlike Experiment 4, the response-stimulus interval was 500 msec. With the same force condition, the instructed sequence patterns were 30%-30% and 50%-50%. With the different force condition, the instructed sequence patterns were 30%-50% and 50%-30%. Subjects performed 50 blocked trials (30 practice trials and 20 test trials) for each of four conditions. Simple RTs below 100 msec. were considered premature reactions and were omitted. Dependent measures were the same as in Experiment 1.

The results of force-time measures were very similar. Only the main effects for target force were significant ( $F(1, 7) = 273.29$  for actual peak force;  $F(1, 7) = 45.73$  for time to peak force;  $F(1, 7) = 47.24$  for force duration,  $ps < .001$ ). This indicates that the 30% condition produced a smaller peak force and shorter time to peak force and force duration than did the 50% condition. With the same force condition, means of actual peak force were 26-28% and 45-47% for the 30-30% and 50-50% conditions, respectively. Means of time to peak force were 96-98 msec. and 113-114 msec. for the 30-30% and 50-50% conditions, respectively. Means of force duration were 226-228 msec. and 255-254 msec. for the 30-30% and 50-50% conditions, respectively. With the

different force condition, means of actual peak force were 29-50% and 48-27% for the 30-50% and 50-30% conditions, respectively. Means of time to peak force were 99-121 msec. and 117-102 msec. for the 30-50% and 50-30% conditions. Means of force duration were 232-271 msec. and 263-235 msec. for the 30-50% and 50-30% conditions, respectively. As is evident in these data, the subjects' mean actual peak force closely matched the target force of 30 or 50%. These findings indicate that subjects were able to meet the task constraints imposed by the experimenter.

The results of the simple RT and premotor time were very similar. The same force conditions produced significantly shorter simple RTs ( $F(1, 7) = 69.49, p < .01$ ) and premotor times ( $F(1, 7) = 40.01, p < .01$ ) than did the different force conditions for the second response. The same force conditions also produced significantly shorter RTs ( $F(1, 7) = 30.82, p < .01$ ) and premotor times ( $F(1, 7) = 25.83, p < .01$ ) for the second response than for the first response. These findings indicate that the repetition effect was found only for the same force conditions. With the same force condition, mean simple RTs were 258-216 msec. and 263-222 msec. for the 30-30% and 50-50% conditions, respectively. Mean premotor times were 214-177 msec. and 216-176 msec. for the 30-30% and 50-50% conditions, respectively. With the different force condition, mean simple RTs were 268-252 msec. and 275-261 msec. for the 30-50% and 50-30% conditions, respectively. Mean premotor times were 221-207 msec. and 225-220 ms for the 30-50% and 50-30% conditions, respectively. The result of the motor time showed that the second response produced significantly shorter motor time than did the first response for both same force and different force conditions ( $F(1, 7) = 19.19, p < .01$ ). This may suggest that the electrical activities of muscle contraction require more motor time when there is no prior response than when there is a prior one. However, the difference in motor time between the first and second responses was too small to account for a substantial repetition effect. Most important, the motor time to initiate the second response did not differ between the same force and different force conditions. This result strongly suggests that the repetition effects observed in Experiment 4 were

due to decreases in time required for response programming. With the same force condition, mean motor times were 45-40 msec. and 47-46 msec. for the 30-30% and 50-50% conditions, respectively. With the different force condition, mean motor times were 45-45 msec. and 50-41 msec. for the 30-50% and 50-30% conditions, respectively. Premature reactions were extremely infrequent as is indicated by the overall mean error rate of 0.3%, which was evenly distributed across all conditions.

### *Discussion*

The findings of Experiment 4 in which the simple RT paradigm was adopted were remarkably different from those of Experiment 2 and 3 in which the choice RT paradigm was adopted. The repetition effect was found for all the repetition conditions in the same force condition. The size of the effect observed was similar across all the repetition conditions. On the contrary, the repetition effect vanished completely across all the repetition conditions in the different force condition. The supplementary experiment clearly demonstrated that the repetition effect obtained in the same force condition was due to the decreases in premotor times but not in motor times. The result on motor time rules out the possibility that the repetition effect observed was due simply to decreases in time required for the electrical or physiological activity associated with muscle contraction. Since premotor time is a more valid indicant of the time needed for central information processing than RT (Fischman, 1984; Weiss, 1965), the present findings strongly suggest that the repetition effect seen in simple RT is not peripheral but central, in origin. The results of Experiment 4 speak against both the perceptual speedup hypothesis and the response selection shortcut hypothesis proposed by Pashler and Baylis's (1991b). If these hypotheses were applied to the simple RT situation, then the stimulus repetition effect should have been found for the different force condition, which was not the case. Thus, the results of Experiment 4 suggest that when the same responses are repeated under the simple RT condition, response programming is the

primary locus of the repetition effect.

### Conclusion

Chapter 3 examined the possibility that the repetition effect occurs at the stage of response programming, by conducting four experiments. To test this hypothesis, the present experiments examined what happens on the RT to initiate the second response when two serial responses are comprised of the same or different responses in their force-time patterns, or more specifically, they are comprised of the same or different responses in their motor programs. The task used was an isometric force-production task. Subjects were required to react and produce the sequence of the same or different force by squeezing the handle as quickly and accurately as possible after the first and second reaction signals that are presented in rapid succession. It was assumed that the repetition effect occurs only when the same force response is repeated on successive responses, because the motor program for the preceding response could be reused for the next response.

Experiment 1 examined whether varying force magnitude influences the RTs in both simple and choice paradigms. The RT to initiate force response did not change across the range of forces examined in both simple and choice RT conditions, regardless of whether a desired force was selected by the experimenter or by the subject. These findings suggested that the time required to program force response is invariant across the range of forces examined.

Experiment 2 examined the effect of the similarity of serial force responses on repetitions with a noncategorizable mapping in a choice RT paradigm. Experiment 3 examined the effect of the similarity of serial responses on repetitions with a categorizable mapping in a choice RT paradigm. Consistent with the results reported by Pashler and Baylis (1991b), both experiments showed repetition effects only for stimulus repetition when the different response or free response was repeated on

successive responses, regardless of categorizability of the stimuli. These findings supported the response-selection hypothesis of the repetition effect. When the same force response was repeated, however, repetition effects were observed not only for stimulus repetition but also for nonrepetition. These findings were interpreted as evidence for two loci of the repetition effect, response selection and response programming.

Finally, Experiment 4 examined the effect of the similarity of serial responses on repetition effects in a simple RT paradigm. When the same force response was repeated on successive responses, repetition effects were found for all of the stimulus repetition, response repetition, and nonrepetition. When the different force response was repeated, on the contrary, repetition effects vanished completely across all the repetition conditions. Thus, the results of Experiment 4 suggested that when the same responses are repeated under the simple RT condition, response programming is the primary locus of the repetition effect.

In conclusion, experiments in Chapter 3 suggested that if the same response is repeated on successive responses, in a serial choice-RT situation, repetition effects originates in both response selection and response programming, whereas in a serial simple-RT situation, response programming is the primary locus of the repetition effect.

## CHAPTER 4

### NATURE OF REPETITION EFFECT AT STAGE OF RESPONSE PROGRAMMING

The results of the experiments in Chapter 3 suggested two loci of the repetition effect, response selection and response programming. That is, if the same response is repeated on successive responses, in a serial choice RT situation, response selection is the primary locus of the repetition effect and response programming is the secondary locus of the effect. In a serial simple RT situation, however, response programming is the primary locus of the repetition effect.

At this point, two questions emerge concerning the nature of the repetition effect that arises from response programming. The first question deals with whether the repetition effect that arises from response programming is due to a speedup of the processing or bypassing of the processing. By a speedup, Pashler and Baylis (1991b) meant that when the repeated event reuses the same processing as the previous trial, the processing at the relevant stage progresses but proceeds more quickly than the normal processing. By bypassing, on the other hand, they meant that when the repeated event reuses the same processing as the previous trial, the processing at the relevant stage is entirely eliminated. For example, the response selection shortcut hypothesis put forward by Pashler and Baylis (1991b) proposed that bypassing of response selection occurs from direct access to the last stimulus-response connection or memory trace. That is, after making a particular stimulus-response pairing, the stimulus-response connection or memory trace is activated. When the stimulus is presented again, the connection or memory trace has direct access that eliminates need to search through memory for the

correct response. This view is consistent with Keele's (1969) and Smith's (1968) view for the repetition effect on the basis of short-term memory. As mentioned in Chapter 1, on the other hand, alternative models have been proposed to account for the response programming process (e.g., Klapp, 1976; Rosenbaum, Hindorff, & Munro, 1987; Rosenbaum, Inhoff, & Gordon, 1984; Schmidt, 1975; Sternberg et al., 1978). Though these models present some competing views, they have the common view that a constructed motor program is temporarily stored in a short-term motor output buffer just before execution. Therefore, if the motor-program representation has direct access, then this may act so that the normal response programming is bypassed (response programming bypass hypothesis). Or the processing at the response programming-stage may merely proceed more quickly than the normal processing (response programming speedup hypothesis). In Experiment 5, these alternative hypotheses are tested.

The second question deals with how long the repetition effect that arises from response programming is retained. As reviewed in Chapter 2, the repetition effect depends on response-stimulus interval or intertrial interval. The size of the effect is particularly marked when the response-stimulus interval or intertrial interval is within 1 sec. (Bertelson, 1961; Bertelson & Renkin, 1966; Entus & Bindra, 1970; Hale, 1967), and decreases as the interval increased. For example, Keele (1969) and Smith (1968) found that the repetition effect decreases as the intertrial interval increased from 2 to 4 sec. With longer response-stimulus interval or intertrial interval beyond these intervals, there was no repetition effect. These results may suggest that the first few seconds would be the approximate upper limit for the retention of the repetition effect that arises from response selection, because Campbell and Proctor (1993) and Pashler and Baylis (1991b) found that the primary locus of the repetition effect is response selection. However, it is unclear how long the repetition effect that arises from response programming is retained. Thus, in Experiment 6, short-term retention of the repetition effect that arises from response programming is examined.

In both experiments that follow, the simple RT paradigm is adopted because the

result of Experiment 4 suggested that in a serial simple RT situation, the primary locus of the repetition effect is response programming. If the choice RT paradigm was used, the effect that stems from response programming would be confounded with the effect that stems from response selection. In addition, as in Experiment 1 and 4, the EMG technique was employed to separate premotor and motor time effects.

### Experiment 5

The present experiment is conducted to examine whether the repetition effect that arises from response programming is due to a speedup of the processing (response programming speedup hypothesis) or bypassing of the processing (response programming bypass hypothesis).

To test these alternative hypotheses, the psychological refractory period paradigm is adopted. In this paradigm, subjects are presented two stimuli in rapid succession, with each stimulus requiring a quick, discrete response. The typical finding is that the RT to the second of the two stimuli is considerably delayed, compared with the RT to the same stimulus when it is presented alone and more so when the interstimulus interval is shorter. The delay is usually observed for the interstimulus intervals up to 200 or 300 msec. This phenomenon, which has been called the *psychological refractoriness effect* by Telford (1931), demonstrates a severe limitation in people's ability to perform two RT tasks at the same time (for reviews, see Sanders, 1998; Smith, 1967; Welford, 1980). At first glance, one might suppose that the paradigm of psychological refractory period is the same as the paradigm of repetition effect because both involve serial reactions in common. Unlike in the repetition effect paradigm, however, in the psychological refractory period paradigm the second stimulus is in almost all cases presented before the initiation of the first response or during the execution of the first response. Furthermore, the two stimuli are presented in different modalities (e.g., auditory-visual design) and require responses by different hands to

eliminate perceptual interference and structural interference. Thus, no repetition effect should be expected.

Though several theories have been put forward to account for the psychological refractoriness effect, the most persuasive and comprehensive explanations have been provided by single-channel theories. These theories propose that somewhere in the central processing stages there is a single-channel bottleneck that cannot process more than one task at a time. When the processing stage is occupied with a first task, processing a second task must be postponed until the stage becomes available. Thus, the RT to the second stimulus is delayed compared with the control RT when it is presented alone.

The major alternatives to single-channel theories are those of expectancy and capacity sharing. Expectancy theory states that the delay is due to the fact that the subject is not ready or does not expect the second stimulus so soon after the first stimulus (Adams, 1962). The weakness of the theory is the inability to explain the finding that the same delay is observed even when interstimulus interval is kept constant. Capacity-sharing theory proposes that the delay originates not in postponement of the information processing at particular stages but rather in a depleted sharing of capacity or resources between the first and second responses (Gottsdanker, 1979; McLeod, 1977). While the theory predicts that the RT delay is observed not only for the second response but also for the first response, the RT delay for the first response is always found by no means. Thus, these theories are not as comprehensive as single-channel theories.

Single-channel theories differ with respect to the locus of the bottleneck in the chain of processes. One view is that the bottleneck is at the stage of perceptual processing (Broadbent, 1958). Another is that the bottleneck occurs at the stage of response selection (McCann & Johnston, 1992; Pashler, 1984, 1989; Pashler & Johnston, 1989; Smith, 1967; Welford, 1952, 1980). Still another is that the bottleneck arises in the stage of response programming (De Jong, 1993; Keele, 1973; Netick & Klapp, 1994). However, the views that have received the most consistent empirical support are

the response selection bottleneck and response programming bottleneck views. For example, Logan and Burkell (1986) and Pashler and Johnston (1989) found no psychological refractoriness effect when the first stimulus was presented but did not require an overt response. This finding suggests that the perceptual processing of the second stimulus can proceed in parallel with the first-task processing, speaking against the perceptual bottleneck view. McCann and Johnston (1992) and Pashler (1984, 1989) found that the effects of the difficulty of response selection such as stimulus-response compatibility on choice RT were additive with the effects of interstimulus interval. Since it is well known that stimulus-response compatibility effects are confined to the response selection stage (e.g., Shúlman & McConkie, 1973; Sternberg, 1969), this result supports the view of the response selection bottleneck. The most important finding for the purpose of the present study is, however, that even when a simple RT paradigm was used, psychological refractoriness effect has been found (e.g., Davis, 1957, 1959; Karlin & Kestenbaum, 1968; Klemmer, 1956; Kroll, 1961; Slater-Hammel, 1958; Telford, 1931). As discussed in Chapter 3, during simple RT, response selection is not needed because subjects know the required response before the starting signal is presented. Thus, this result strongly suggests that under the simple RT circumstances, the bottleneck is at the response-programming stage.

Given that the simple RT circumstances directly reflect the existence of the response programming bottleneck, one way to test the present alternative hypotheses by using this paradigm is to observe what happens on the simple RT when the similarity of serial responses is manipulated, as in Experiment 4. In this case, one plausible prediction, consistent with the previous evidence, is that when serial responses contain different motor programs, a typical refractoriness effect would be observed. This is because only one motor program can be constructed at a time and thus the normal programming for the second response cannot begin until the programming for the first response is completed. When repeated responses contain the same motor programs, on the other hand, if the response programming speedup hypothesis is correct, the

refractoriness effect would still be observed, but the size of the effect should be smaller than for the different motor program condition. Thus, it is expected that the simple RT to initiate the second response is longer than for the control condition, but is shorter than for the different motor program condition. This is because that the response programming for the second response is subject to postponement, but proceeds more quickly than the normal processing. On the contrary, if the response programming bypass hypothesis is correct, the refractoriness effect should vanish and instead the repetition effect may be observed. Thus, it is expected that the simple RT to initiate the second response is shorter than for both the different motor program and control conditions. This is because the normal response programming is bypassed by accessing directly to the motor-program representation and is not subject to the response programming bottleneck.

### *Method*

*Subjects.* Ten graduate and undergraduate students (4 women and 6 men), ranging in age from 20 to 24 years, with a mean of 21.8 yr., volunteered to serve as subjects. They all wrote with their right hands. None had prior knowledge of the hypotheses being tested.

*Apparatus.* The apparatus was the same as in Experiment 1 except that a light stimulus generator (Takei 331) was used to present a red light as a reaction signal. The rise time of the stimulus was approximately 50 msec.

*Design.* The design of the experiment was a 3 x 7 (serial pattern x interstimulus interval) factorial with repeated measures on all factors. The first factor had three levels of the same force, different force, and control conditions. The second factor had seven levels of 50, 100, 200, 500, 1,000, 2,000, and 4,000 msec.

*Procedure.* The procedure was almost the same as in Experiment 4 except that a general psychological refractory period paradigm was used. The task was to react and produce the sequence of the same or different peak force by squeezing the handle as quickly and accurately as possible after each of two stimuli separated by variable interstimulus intervals.

Each trial began with a warning signal of 300-msec. duration, followed by an auditory stimulus (1,000 Hz) of 100-msec. duration with a fixed foreperiod of 1,000 msec. This stimulus served as the signal for the subjects to initiate a first response with the left hand. Following variable interstimulus intervals (50, 100, 200, 500, 1,000, 2,000, or 4,000 msec.), a red light stimulus of 100-msec. duration was presented which was the signal to initiate a second response with the right hand.

There were two experimental conditions: same force and different force. With the same force condition, the instructed sequence patterns were 30%-30% of the maximum of the isometric grip strength of each subject. The subjects were instructed to reproduce the same force as in the first response, whether or not they felt that the peak force produced in the first response deviated from the required force. With the different force condition, the instructed sequence patterns were 50%-30%. In addition, there was a control condition for the second response. In this condition, the first stimulus was omitted, and subjects made only one response to the red stimulus that occurred after one of the seven interstimulus intervals. In addition, there were two control conditions for the first response. In these conditions, the second stimulus was omitted, and subjects made only one response by producing either 30 or 50% force to the first stimulus that occurred with a fixed foreperiod of 1,000 msec.

Subjects participated in four consecutive daily sessions. The first session provided equal practice for the various force conditions. In each session, 2 through 4, subjects were assigned to one of the two experimental conditions and a control condition for the second response. One of the two control conditions for the first response was randomly assigned somewhere from Session 2 through 4. The conditions

were randomly ordered for each subject. Subjects performed 50 blocked trials (30 practice trials and 20 test trials) for each interstimulus interval in the daily session. The seven interstimulus interval conditions were randomly ordered for each subject. The intertrial interval was 10 sec. A 3-min. break was given every 10 trials. Each interstimulus interval condition was run at 5-min. intervals. A 2-hr. break was given after the completion of the first four interstimulus interval conditions. RTs below 100 msec. were considered premature reactions and were omitted. All test trials on which premature reaction errors occurred were repeated at the end of the condition in which they occurred. The other procedure was the same as in Experiment 4.

*Dependent measures.* The dependent measures were the same as in Experiment 1. Unlike the experiments in the previous chapter, the first and second stimuli were presented in different modalities (auditory-visual design) and require responses by different hands. Thus, these data were analyzed via a two-way repeated-measure ANOVA with serial pattern and interstimulus interval for each of the first and second responses. All post hoc analyses were performed using the LSD test at the .05 level.

## *Results*

### *First Response*

*Force-time measures.* The results of force-time measures were very similar. ANOVAs showed that only the main effects for serial pattern were significant ( $F(1, 9) = 714.31$  for actual peak force;  $F(1, 9) = 86.81$  for time to peak force;  $F(1, 9) = 55.59$  for force duration,  $ps < .001$ ). Not surprisingly, the same force (30% force) condition produced a smaller peak force and shorter time to peak force and force duration than did the different force (50% force) condition. Means of actual peak force were 30 and 52%,

means of time to peak force were 111 and 131 msec., and means of force duration were 258 and 288 msec., for the same force and different force conditions, respectively. Also, means of actual peak force were 32 and 53%, means of time to peak force were 110 and 132 msec., and means of force duration were 257 and 294 msec., for the control conditions for same force and different force conditions, respectively. As is evident in these data, the subjects' mean actual peak force closely matched the target force of 30 or 50%. Moreover, all of the responses were quite rapid as is indicated by the overall mean time to peak force of 121 msec. These findings indicate that subjects were able to meet the task constraints imposed by the experimenter. The mean maximal isometric grip strength (with standard deviations) were 43.4 kg (7.59) and 47.3 kg (8.43) for the left hand and the right hand, respectively.

*Simple RT and premotor time.* The results of simple RT and premotor time were very similar. ANOVAs showed no main effects for serial pattern or for interstimulus interval as well as nonsignificant interactions between the two factors. These results indicate that all conditions did not differ in both the simple RT and premotor time of the first response. Mean simple RTs were 259, 260, and 255 msec. and mean premotor times were 198, 196, and 193 msec. for the same force, different force, and control conditions, respectively.

*Motor time.* The ANOVA showed no main effects for serial pattern or for interstimulus interval as well as nonsignificant interaction between the two factors. Mean motor times were 62, 64, and 62 msec. for the same force, different force, and control conditions, respectively.

*Errors.* Premature reactions were extremely infrequent as is indicated by the over-all mean error rate of 0.7%, which was evenly distributed across all conditions.

### *Second Response*

*Force-time measures.* The results of force-time measures were very similar. ANOVAs showed no main effects for serial pattern or for interstimulus interval as well as nonsignificant interactions between the two factors. These results indicate that the second response was the same in terms of force-time patterns across all conditions. Means of actual peak force were 29, 29 and 29%, means of time to peak force were 81, 85, and 79 msec., and means of force duration were 182, 189, and 178 msec., for the same force, different force, and control conditions, respectively. As is evident in these data, the subjects' mean actual peak force closely matched the target force of 30% and all of the responses were rapidly executed. Additionally, for both experimental conditions, the force-time measures for the second response were compared with those for the first response. With the different force condition, as expected, the first response produced a larger peak force and longer time to peak force and force duration than did the second response. With the same force condition, actual peak force did not differ between the first and second responses, whereas time to peak force and force duration were significantly shorter for the second response than for the first response. This may have been due to the fact that the handedness takes shorter to make isometric contractions even if serial responses contain the same motor programs. However, overall results indicate that subjects were able to meet the task constraints imposed by the experimenter.

*Simple RT and premotor time.* Figure 6 shows mean premotor time as a function of serial pattern and interstimulus interval for the second response. The results of the simple RT and premotor time were very similar. ANOVAs showed significant main effects for serial pattern ( $F(2, 18) = 21.88$  for simple RT and  $F(2, 18) = 26.77$  for premotor time,  $ps < .001$ ) and for interstimulus interval ( $F(6, 54) = 14.99$  for simple RT and  $F(6, 54) = 15.40$  for premotor time,  $ps < .001$ ). Interactions between the two factors

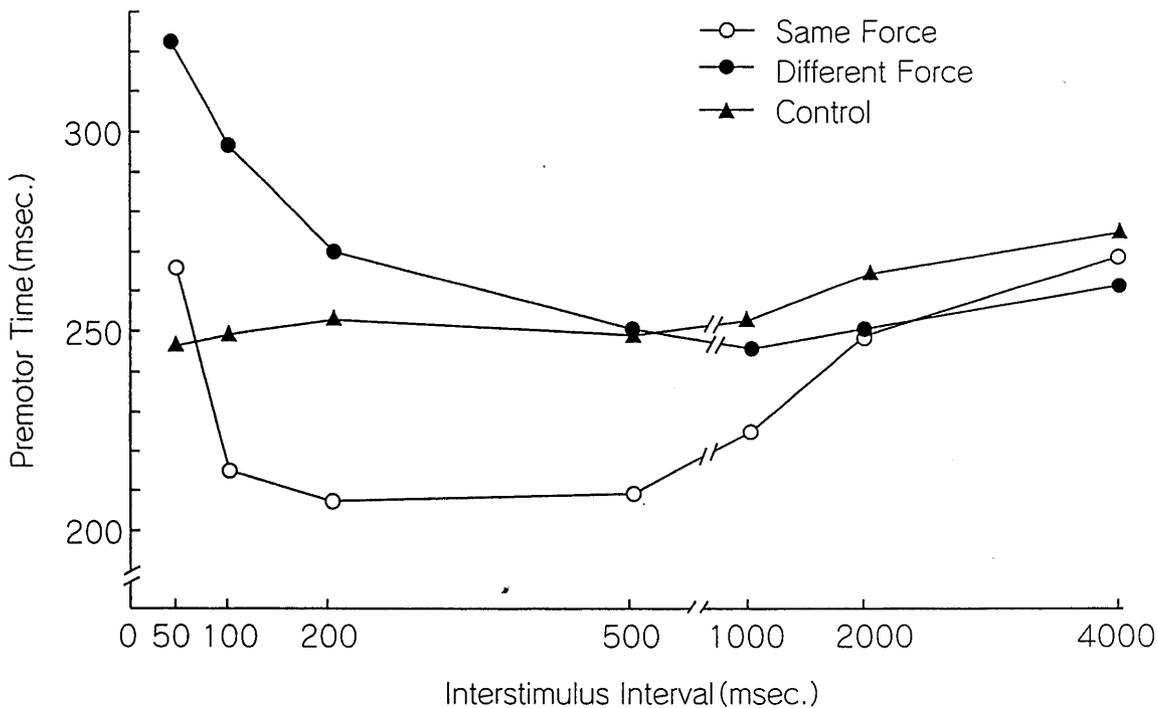


Figure 6. Mean premotor time in Experiment 5 as a function of serial pattern and interstimulus interval for the second response.

were also significant ( $F(12, 108) = 11.44$  for simple RT and  $F(12, 108) = 11.05$  for premotor time,  $ps < .001$ ). Analyses of interactions showed that the different force condition produced significantly longer simple RT and premotor time than did the control condition, with the interstimulus intervals of 50 and 100 msec. However, there were no different simple RT and premotor time between both conditions, with the interstimulus intervals of 200, 500, 1,000, 2,000, and 4,000 msec. Analyses of interactions also showed that the same force condition produced significantly shorter simple RT and premotor time than did the control condition, with the interstimulus intervals of 100, 200, 500, and 1,000 msec. However, there were no different simple RT and premotor time between both conditions, with the interstimulus intervals of 50, 2,000, and 4,000 msec. Moreover, there were no different simple RT and premotor time among all the three conditions, with the interstimulus intervals of 2,000 and 4,000 msec.

*Motor time.* The ANOVA showed no main effects for serial pattern or for interstimulus interval as well as nonsignificant interaction between the two factors. Mean motor times were 38, 36, and 37 msec. for the same force, different force, and control conditions, respectively.

*Errors.* Premature reactions were extremely infrequent as is indicated by the overall mean error rate of 0.5%, which was evenly distributed across all conditions.

### *Discussion*

A typical refractoriness effect was observed for the different force condition, but not for the same force condition. Consistent with the results of the previous research (e.g., Davis, 1957, 1959; Klemmer, 1956; Kroll, 1961), the refractoriness effect was found for the interstimulus intervals up to 200 msec., with no further increases thereafter compared with the control condition. As expected, the results of simple RT and premotor time were parallel, but the same pattern was not evident for motor time. Since premotor time is regarded as the central component of total RT while motor time is regarded as the peripheral component of total RT, these findings suggest that the observed refractoriness effect was mediated by central rather than peripheral process. These results argue against the view that the bottleneck is associated with response execution per se (e.g., Logan & Burkell, 1986). If this is correct, the results of simple RT and motor time should have been parallel. However, motor time did not differ among all the interstimulus intervals. The present results also argue against expectancy and capacity-sharing theories. Expectancy theory (Adams, 1962) states that the RT delay of the second response is due to subject's subjective uncertainty as to when the second stimulus will arrive. In this experiment, however, the RT and premotor time delay of the second response were generated even when the interstimulus interval was kept constant within each interstimulus interval condition. Capacity-sharing theory

(McLeod, 1977) predicts not only RT delay of the second response but also RT delay of the first response since the first and second responses are assumed to be performed with depleted allocations of capacity. However, the results of RT, premotor time, and motor time for the first response showed nonsignificant effect for interstimulus interval as well as nonsignificant interaction between two factors.

The present results support the view that under the simple RT circumstances, the single channel bottleneck is at the response-programming stage (e.g., Davis, 1957, 1959; Karlin & Kestenbaum, 1968; Klemmer, 1956; Kroll, 1961; Telford, 1931). It should be noted here that the only variation between the same force and different force conditions was in the nature of the response. If the bottleneck was at another stage, the refractoriness effect should have been observed regardless of whether serial responses were the same or different. This was not the case. Thus, the refractoriness effect found for the different force condition may be accounted for the fact that only one motor program can be constructed at a time and thus the normal programming for the second response cannot begin until the programming for the first response is completed.

The most important finding for the present purpose is that the same force condition produced significantly shorter simple RT and premotor time than did the control condition when the interstimulus intervals were from 100 to 1,000 msec. This suggests the presence of a repetition effect. Thus, these results argue in favor of the response programming bypass hypothesis that the repetition effect that arises from response programming is due to bypassing of response programming processing. This bypassing may be explained in terms of direct access to the motor-program representation in the motor output buffer. The repetition effect that is due to bypassing could be observed as long as the motor-program representation is still alive. However, when the representation decays at some value of interval, the second response would need a time-consuming reprogramming operation. The present result might suggest that the approximate upper limit for the retention of a motor program representation is the first few seconds. In Experiment 6, short-term retention of a motor program

representation will be discussed in detail.

The unexpected result of the present experiment is that the simple RT and premotor time for the interstimulus interval of 50 msec. did not differ between the same force and control conditions. This might suggest that this delay reflects some constraints in evocation process of motor command; when two motor commands are evoked in rapid succession, the evocation of the second motor command cannot begin until about 50 msec. after the first command is evoked.

Taken together, the present experiment suggests that that under the simple RT circumstances, the single channel bottleneck is at the response-programming stage, and the repetition effect that arises from response programming is due to bypassing of the processing of response programming.

#### Experiment 6

The results of Experiment 5 supported the view that the repetition effect that originates in response programming occurs from bypassing of the normal response programming. This bypassing was explained in terms of direct access to the motor-program representation in the motor output buffer. The present experiment was conducted to examine how long the repetition effect that arises from response programming is retained, or more specifically, how long a constructed motor program is retained in the motor program output buffer. One way to examine this is to observe the effects of variations in interval between the first and second responses on simple RT to initiate the second response when serial responses are comprised of the same responses. It is expected that the simple RT to initiate the second response would be nearly maximized at the retention interval at which the repetition effect vanishes, with no further increases thereafter. This is because when the motor program representation of the first response would be no longer available, the second response would need a reprogramming operation.

### *Method*

*Subjects.* Twelve undergraduate students (6 women and 6 men), ranging in age from 19 to 23 years, with a mean of 21.4 yr., volunteered to serve as subjects. They all wrote with their right hands. None had prior knowledge of the hypotheses being tested.

*Apparatus.* The apparatus was the same as in Experiment 1 except that a light stimulus generator (Takei 331) was used to present a red and a green light. The rise time of the stimulus was approximately 50 msec.

*Design.* The design of the experiment was a repeated measure design with seven retention intervals of 0, 1, 2, 3, 4, and 5 sec., and a control condition.

*Procedure.* The procedure was almost the same as in the supplementary experiment of Experiment 4, unless noted otherwise. The task was to react and produce the sequence of the same force by squeezing the handle with the right (preferred) hand as quickly and accurately as possible after each of two red stimuli separated by variable retention intervals.

Each trial began with a warning tone of 300-msec. duration, followed by a first red light stimulus of 200-msec. duration with a fixed foreperiod of 1,000 msec. This stimulus served as the signal for the subjects to initiate a first response with the right hand. Following a variable retention interval after the completion of the first response, a second red light stimulus of 200-msec. duration was presented, which was the signal to initiate a second response with the right hand. The instructed sequence pattern was 30%-30% of the maximum of the isometric grip strength of each subject. The subjects were instructed to reproduce the same force as in the first response, whether or not they felt that the peak force produced in the first response deviated from the required force.

The retention intervals were 0, 1, 2, 3, 4, and 5 sec. Retention interval was defined as the time between the termination of the first response and the presentation of the second red stimulus. Termination of the first response was defined as the point in time that the value recorded from dynamometer fell below 0.3 kg. A control condition was set to examine the net programming time for the second response. In this condition, the first stimulus was omitted, and subjects were required to make only one response to the red stimulus that occurred with random foreperiod of 0, 1, 2, 3, 4, and 5 sec. For the second response (the first response for the control condition), catch trials (by use of go/no-go paradigm) were included at a rate of one-sixth of the trials to discourage subjects from anticipating the initiation stimulus. On catch trials, a green stimulus of 200-msec. duration instead of the second red stimulus was generated, which was the signal not to respond.

Subjects participated in three consecutive daily sessions. The first session provided equal practice for the various retention interval conditions. From session 2 through session 3, subjects performed 30 consecutive trials (10 practice trials and 20 test trials) for each of six retention intervals and a control condition (five trials at each retention interval). The order of the seven conditions was randomly determined for each subject. Each condition was run at 1-hr. intervals. The intertrial interval was 10 sec. A 3-min. break was given every 12 trials. Simple RTs below 100 msec. were considered premature reactions and were omitted. All test trials on which premature reactions occurred were repeated at the end of the trial block in which they occurred.

*Dependent measures.* The dependent measures were the same as in the supplementary experiment of Experiment 4 except that premotor time and motor time were measured only for the second response. These data were analysed via a one-way repeated measure ANOVA. All post hoc analyses were performed using the Newman-Keuls test at the .05 level.

## *Results*

### *First Response*

*Force-time measures.* The results of force-time measures were very similar. ANOVAs showed no significant difference among retention interval conditions. These results indicate that the first response was the same in terms of force and time patterns across all conditions. Subjects' mean actual peak force for each condition closely matched the expected force, as is indicated by the overall mean actual peak force of 23%. Moreover, all of the responses were quite rapid, as is indicated by the overall mean time to peak force of 96 msec. and mean force duration of 222 msec. These findings indicate that subjects were able to meet the task constraints imposed by the experimenter. The mean maximal isometric grip strength (with standard deviation) was 44.6 kg (12.96) for the right hand.

*Simple RT.* The ANOVA showed no significant difference among retention interval conditions. Mean simple RT was 322 msec.

*Errors.* Premature reactions were extremely infrequent as is indicated by the overall mean error rate of 0.1%, which was evenly distributed across all conditions.

### *Second Response*

*Force-time measures.* The results of force-time measures were very similar. ANOVAs showed no significant difference among retention interval conditions. These results indicate that the second response was the same in terms of force and time patterns across all conditions. Subjects' mean actual peak force for each condition closely matched the expected force, as is indicated by the overall mean actual peak

force of 26%. Moreover, all of the responses were quite rapid, as are indicated by the overall mean time to peak force of 97 msec. and mean force duration of 220 msec. Though supplementary analyses were performed to compare the force-time measures for the second response with those for the first response, no significant differences were found between the first and second responses. These findings indicate that subjects were able to meet the task constraints imposed by the experimenter.

*Simple RT and premotor time.* Figure 7 shows mean premotor time as a function of retention interval for the second response. The results of the simple RT and

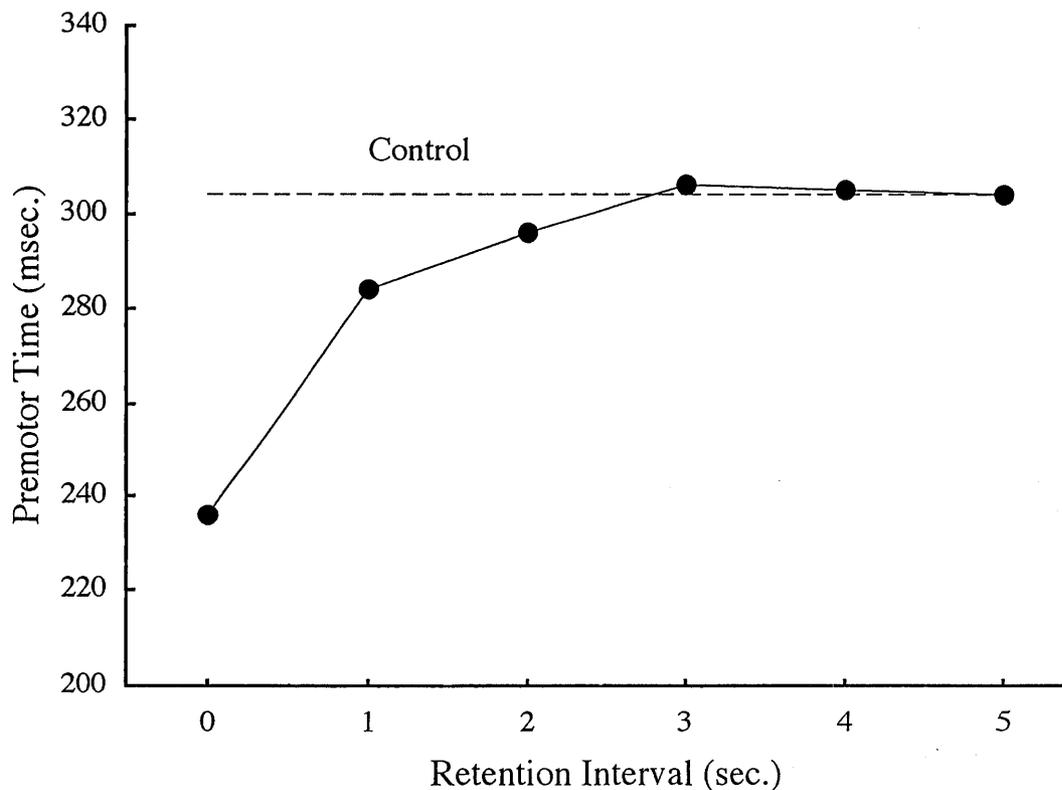


Figure 7. Mean premotor time in Experiment 6 as a function of retention interval for the second response.

premotor time were very similar. ANOVAs showed significant effects of experimental conditions ( $F(6, 66) = 24.51$  for simple RT and  $F(6, 66) = 22.85$  for premotor time  $p < .001$ ). Post hoc analyses showed that the 0-sec. condition produced shorter simple RT

and premotor time than did all other conditions, and that the 1-sec. condition produced shorter simple RT and premotor time than did the 3-sec., 4-sec., 5-sec., and control conditions. There were no significant simple RT and premotor time differences between the 1-sec. and 2-sec. conditions and no significant differences among the 2-sec., 3-sec., 4-sec., 5-sec., and control conditions. Some tendency was noted, for as the length of the retention interval increased from 0 to 2 seconds, simple RT and premotor time increased sharply, with no further increases thereafter.

*Motor time.* Analysis of motor times showed a significant effect of retention condition ( $F(6, 66) = 6.61, p < .001$ ). Post hoc analysis showed that the control condition produced longer motor time than did all other conditions, which were not significantly different from each other. This result, consistent with the result of Experiment 4, may suggest that the preparation of a force-production response take more motor time when the force response has no prior force response than when there is prior force response, separated by a shorter time interval. Mean motor times were 57 and 62 msec. for the retention interval and control conditions, respectively.

*Errors.* Premature reactions were extremely infrequent as is indicated by the overall mean error rate was below 0.2% which was evenly distributed across all conditions. Examination of the catch trials indicated that false starts were produced at a slightly high rate, as is indicated by the overall mean error rate of 14.6%. However, the analysis showed no significant difference among all conditions.

### Discussion

The purpose of Experiment 6 was to examine the retention time of the repetition effect that arises from response programming. The results indicated that the simple RT and premotor time to initiate the second response increased sharply as the

length of the retention interval increased from 0 to 2 seconds, with no further increases thereafter. Simple RTs and premotor times for the 2-, 3-, 4-, and 5-sec. conditions were not significantly different from those for the control condition. The differences in motor time across the six retention-interval conditions were too small to account for the substantial RT differences. These findings are similar to those observed for the same force condition in Experiment 5. Thus, these findings may suggest that the repetition effect that arises from response programming would retain within the first 2 seconds, which may be the approximate upper limit for the retention of the repetition effect that arises from response programming. Given that the repetition effects observed in simple RT stem from direct access to the motor-program representation, the present results may also suggest that nearly all the decay of a motor-program representation occur within the first 2 seconds. On the other hand, research on short-term motor memory has made it clear that received sensory information is retained for approximately 30 seconds (e.g., Adams & Dijkstra, 1966; Ito, 1986; Pepper & Herman, 1970). This duration is much longer than the duration of 2 seconds found in the present experiment. This may suggest that the buffer for just-received sensory information (short-term motor memory) and the buffer for forthcoming movements (short-term motor output buffer) exist independently.

There have been some arguments concerning why subjects cannot carry out programming in advance of the simple RT interval, even though subjects know the required response before the signal is presented. Two possible reasons have been put forward by some researchers. First, constructing a motor program might automatically lead to response execution. If the response programming takes place before the signal, subjects would respond erroneously on catch trials. To avoid this, programming must await the signal (Sternberg et al., 1978). The second possibility is that a constructed motor program stored in a motor output buffer might be subject to rapid decay, in which case the motor program would have to be set up immediately before use (Canic & Franks, 1989; Ito, 1991; Sternberg et al., 1978; Verwey, 1994). The present result appears to lend some support for the view that programming delay found in simple RT

circumstances is due to rapid decay of a constructed motor program

Another interesting aspect of present data was that simple RT and premotor time increased linearly as the retention interval increased from 0 to 2 sec. According to the decay theory in short-term motor memory (e.g., Adams, 1967), it might be argued that, as a programmed representation (memory trace) loses its strength with time, more time is required to prepare for response. If this is the case, a question is why would decay of the programmed representation lead to increases of simple RT and premotor time? One possibility might be that the weaker representation requires more time to transform it into the actual signals to be relayed to the muscles. If this is correct, the weaker representation would have resulted in more deviated force from the target force. However, analyses showed no significant variability for all of force-time measures across all retention interval conditions. Another possibility might be that the weaker representation requires more time to repair decaying motor program and revive the original motor program. Further investigation is needed to examine these possibilities.

The negatively accelerated retention curve found in the present experiment is consistent with the view of a decaying memory trace (Adams & Dijkstra, 1966; Brown, 1958; Peterson & Peterson, 1959). This is not to say that other sources of forgetting, such as interference in the event of stimulus processing, are not operating. However, note that in the present experiment, the stimulus and response conditions were held constant across all conditions except that the retention interval was manipulated. Therefore, it seems to be unlikely that a prior motor response acting proactively on the following motor response or simple waiting behavior during the retention interval acting retroactively would explain the present results.

In summary, the present findings suggest that the repetition effect that arises from response programming would retain within the first two seconds, which may be the approximate upper limit for the retention of the repetition effect that arises from response programming.

## Conclusion

Experiment 5 in Chapter 4 examined whether the repetition effect observed in simple RT situation is due to a speedup or bypassing of the processing of the response programming. One way to test these alternative hypotheses was to observe what happens on the simple RT when the similarity of serial responses was manipulated, using a psychological refractoriness paradigm. One plausible prediction was that when the different force response is repeated on successive responses, a typical refractoriness effect that the RT to the second of the two stimuli is considerably delayed would be observed. When the same force response is repeated on successive responses, on the other hand, if the response programming speedup hypothesis is correct, then the refractoriness effect should still be observed, but the size of the effect should be smaller than for the different force condition. If the response programming bypass hypothesis is correct, the refractoriness effect should vanish and instead the repetition effect may be observed. The results clearly supported the response programming bypass hypothesis that the repetition effect that originates in response programming is due to bypassing of the normal response programming.

Experiment 6 in Chapter 4 examined how long the repetition effect that arises from response programming is retained, or more specifically, how long a constructed motor program is retained in the motor program output buffer. One way to examine this was to observe the simple RT to the second of the two signals when subjects were required to repeat the same response to each of two reaction signals separated by a variable time interval. It was expected that the simple RT to initiate the second response would be nearly maximized at the retention interval at which the repetition effect vanishes. Result showed that the simple RT to initiate the second response increased sharply as the length of the retention interval increased from 0 to 2 sec., with no further increases thereafter. These findings were interpreted suggesting that the repetition effect that arises from response programming may be retained within the first 2 seconds,

which may be the approximate upper limit for the retention of the constructed motor program.

## CHAPTER 5

### IMAGINED MOVEMENT AND REPETITION EFFECT AT STAGE OF RESPONSE PROGRAMMING

Thus far, the discussion concerning the association between the repetition effect and response programming was restricted to the situation that responses are physically performed. However, one can not only actually perform movements but also imagine performing movements. The latter way of performing movements has been often referred to as *mental practice* (Corbin, 1972; Cratty, 1973; Feltz & Landers, 1983; Richardson, 1969). Richardson (1969) defined mental imagery as quasi-sensory and quasi-perceptual experiences of which persons are self-consciously aware and which exist for persons in the absence of those stimulus conditions that are known to produce their genuine sensory and perceptual counterparts. On the process of the generation of mental imagery, Kosslyn (1975) proposed that mental imagery is generated from abstract units based on perceptual experience that are stored in long-term memory. The question of interest here is whether response programming occurs when movements are imagined as well as when movements are actually performed. If so, it is reasonable to think that the repetition effect that stems from response programming may be observed even when responses are imagined.

One line of support for the possibility that response programming occurs when movements are imagined comes from studies showing that minimal EMG activity accompanies imagery of movement (e.g., Harris & Robinson, 1986; Jacobson, 1932; Ulich, 1967). Since this associated neuromuscular activity could be considered as a correlate of the commands in the motor program for the movement, these findings may

be interpreted as suggesting that response programming may occur when movements are imagined. However, other studies reported that the muscle innervation as a result of imagined movement was not localized to the muscle groups thought to be involved in the actual movement (Hale, 1982; Shaw, 1938). Thus, drawing a conclusion from the association between imagined movement and neuromuscular activity appears unwarranted.

Another line of support for this assumption comes from study in which blood flow in the brain is monitored through the use of positron emission tomography (PET) scans. For example, Roland, Larsen, Lassen, and Skinhoj (1980) found that, regardless of whether a subject performed a finger movement actually or imagined it, the amount of blood flow to the supplementary motor cortex increased. Since there seems to be general agreement that the supplementary motor cortex is involved in the movement planning (e.g., Brinkman, 1984), this finding suggests that response programming may occur when movements are imagined. However, the time interval from the occurrence of metabolic or electrical activity to the initiation of movement is much longer than the choice RT or the simple RT that was used as a behavioral measure of time required for response programming (Deecke, Scheid, & Kornhuber, 1969). Thus it remains unclear whether these physiological data reflect a programming process that occurs during the RT interval, a higher-level cognitive process, or both.

Two experiments reported here are conducted to clarify the functional equivalence for response programming of actually performing versus imagining movements, by showing that the repetition effect that stems from response programming occurs when responses are imagined.

### Experiment 7

To test the hypothesis that response programming occurs when responses are imagined, a serial simple RT procedure as in Experiment 4-6 but a slightly modified

simple RT procedure was adopted. The procedure was to examine the simple RT to initiate the second response when the first response is covertly performed, but the second response is actually performed, with the interstimulus interval less than 2 seconds. The results of Experiment 4-6 indicated that the repetition effect observed in simple RT situation is predominantly due to bypassing of response programming and is retained within the first 2 seconds. Thus, if response programming occurs when movements are imagined as well as when movements are actually performed, the simple RTs to initiate the second response should be shorter for imagining and actually performing the same force response than for imagining and actually performing different force response or the control condition. If such effects would be observed, these findings should be interpreted as evidence for functional equivalence for response programming of actually performing versus imagining movements.

### Method

*Subjects.* Twelve graduate and undergraduate students (7 women and 5 men), ranging in age from 19 to 36 years, with a mean of 22.6 yr., volunteered to serve as subjects. They all wrote with their right hands. None had prior knowledge of the hypotheses being tested.

*Apparatus.* The apparatus was almost the same as in Experiment 1 except that the EMG apparatus was not used.

*Design.* The design of the experiment was a repeated measure design with four experimental conditions and a control condition.

*Procedure.* The procedure was almost the same as in the supplementary experiment of Experiment 4, unless noted otherwise. The task was to react and produce

the sequence of the same or different force by squeezing the handle with the right (preferred) hand as quickly and accurately as possible after each of two red stimulus.

Each trial began with a warning tone of 300-ms duration, followed by a first red light of 100-msec. duration that occurred with a fixed foreperiod of 1,000 msec. This stimulus served as the signal for subjects to initiate a first response. Following a 1,000-msec. interval after the presentation of the first red light, a second red light of 100-msec. duration was presented, which was the signal to initiate a second response.

There were four experimental conditions, actual same force, imagined same force, actual different force, and imagined different force. With the actual same force condition, the instructed sequence patterns were 30%-30% of the maximum of the isometric grip strength of each subject. Subjects were required to produce the 30% force to both the first and second reaction signals. The procedure for the imagined same force condition was the same as in the actual same force condition except that subjects were instructed to imagine producing the 30% force to the first reaction signal. With the actual different force condition, the instructed sequence patterns were 50%-30%. Subjects were required to produce the 50% force to the first reaction signal and then to produce the 30% to the second reaction signal. The procedure for the imagined different force condition was the same as in the condition with the actual different force condition except that subjects were instructed to imagine producing 50% force to the first reaction signal. In both imagined force conditions, subjects were asked to attempt to feel those sensations that might be expected while executing the actual movement (internal imagery). During imagery response, subjects' eyes were opened and subjects held the handles of the dynamometer. Also, subjects were requested not to make any overt movement. Furthermore, subjects were asked at the end of each imagery trial to rate the vividness of their imagery along a 5-point scale where 1 indicated no image present at all and 5 indicated an image as vivid as that from an actual force production. A control condition was set to examine the net programming time for the second response. In the control condition, subjects made only one response by producing the 30% force to the

reaction signal, which occurred with a fixed foreperiod of 1,000 msec. following the auditory warning signal. It should be noted here that the only difference among all conditions was in the first response, and the second response was identical for all conditions. In the second response, catch trials (by use of go/no-go paradigm) were included at a rate of one-fifth of the trials to discourage subjects from anticipating the reaction signal. On catch trials, a green light of 100-msec. duration was generated, which was the signal not to respond.

Subjects participated in two consecutive daily sessions. The first session provided equal practice for all conditions. In the second session, subjects performed 60 blocked trials (40 practice trials and 20 test trials) for each condition. Catch trials were randomly arranged across each condition and subject. The order of the same and different force conditions and the control condition were counterbalanced. The order of the imagined and actual force conditions were also counterbalanced within each of the same and different force conditions. The intertrial interval was 10 sec. A 10-min. break was given every 25 trials. A 30-min. break was given among the same force, different force, and control conditions.

The RTs below 100 msec. were considered premature reactions and were omitted. All test trials on which premature reaction occurred were repeated at the end of the trial block in which they occurred.

*Dependent measures.* The dependent measures were the same as in Experiment 1 except that simple RT was not separated into premotor time and motor time. These data were analysed via a one-way repeated measure ANOVA. All post hoc analyses were performed using the Newman-Keuls test at the .05 level.

### *Results*

*Force-time measures.* The results of force-time measures on the second

response were very similar. ANOVAs showed no main effect of response condition, indicating that the second response was the same in terms of force-time patterns across all conditions. Subjects' mean actual peak force for each condition closely matched the expected force, as is indicated by the overall mean actual peak force of 31%. Moreover, all of the responses were quite rapid, as is indicated by the overall mean time to peak force of 109 msec. and mean force duration of 248 msec. For both actual movement conditions, the force-time measures for the second response were compared with those for the first response. With the actual different force condition, as expected, the first response produced a larger peak force ( $t(11) = 18.48, p < .001$ ) and longer time to peak force ( $t(11) = 6.64, p < .001$ ) and force duration ( $t(11) = 7.84, p < .001$ ) than did the second response, indicating that the force-time patterns differed between the first and second responses. With the actual same force condition, though time to peak force and force duration did not differ between the first and second responses, actual peak force was slightly smaller for the first response than for the second response ( $t(11) = 5.80, p < .05$ ). However, the difference in peak force found between the first and second responses was too small, as is indicated by the mean peak force difference of 2.6%. Thus, these findings indicate that subjects were able to meet the task constraints imposed by the experimenter. With the actual different force condition, the means of peak force, time to peak force, and force duration were 48%, 129 msec., and 284 msec., respectively. With the actual same force condition, they were 30%, 108 msec., and 252 msec., respectively. In both imagined force conditions, no force was recorded through the electrohandgrip dynamometer in test trials. The mean maximal isometric grip strength (with standard deviation) was 40.8 kg (10.4) for the right hand.

*Simple RT.* The Figure 8 shows mean simple RT as a function of each condition for the second response. The ANOVA indicated a significant main effect of response condition ( $F(4, 44) = 5.18, p < .01$ ). Post hoc analysis showed that the actual same force condition and the imagined same force condition produced significantly

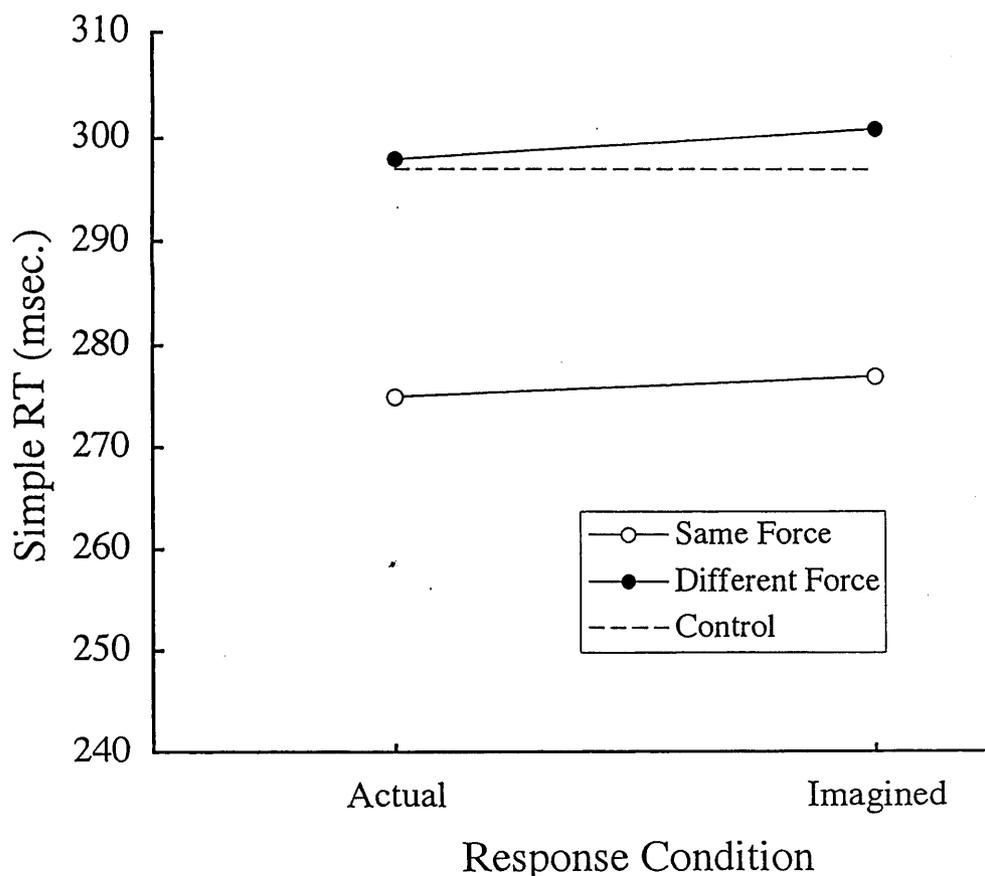


Figure 8. Mean simple reaction time (RT) in Experiment 7 as a function of each condition for the second response.

shorter simple RTs than did all other conditions, which were not significantly different from each other. Moreover, there was no significant difference in simple RT between the actual same force and imagined same force conditions. With the first response, the mean simple RTs were 238 and 247 msec. for the actual same force condition and the imagined same force, respectively, which were not significantly different from each other. The first response produced shorter RT than did the second response, which is no surprise because the first response did not include catch trials.

*Errors.* Premature reactions were extremely infrequent, and the overall mean error rate was less than 0.1% (2 instances in the entire experiment). However, the

catch-trial errors were produced at a high rate, as indicated by the over-all mean rate of 20.7%, but evenly distributed across all conditions. The ANOVA indicated no main effect of response condition.

*Vividness rating of imagery of movement.* The mean vividness score (with standard deviations in parentheses) were 3.3 (0.6) and 3.1 (0.6) for the imagined same force and imagined different force conditions, respectively, which were not significantly different from each other. To examine whether the simple RT to initiate the second response decreases with increases in the vividness score of imagery for the imagined same force condition, within-subject correlations (Pearson  $r_s$ ) were calculated between vividness score and simple RT. The mean correlation coefficients (with standard deviations in parentheses) were -.16 (.25) and -.17 (.19) for the imagined same force and imagined different force, respectively, which were not significantly different from zero.

### *Discussion*

As hypothesized, the repetition effect was found not only for the actual same force condition but also for the imagined same force condition. Simple RTs to initiate the second response were significantly shorter for imagining and actually performing the same force responses than for imagining and actually performing different force responses or the control condition, which were not significantly different from each other. Interestingly, the difference in simple RT between the actual and imagined same force conditions was not significant. There are some implications that mental practice may function as a strategy to set individuals' level of arousal necessary for a good performance (Gould, Weinberg, & Jackson, 1980). If increased arousal level was a cause of the decrement in simple RT, the decrement should have been observed regardless of whether imagined responses were the same or different. However, the data did not support this prediction. Thus, the present findings support the view that response

programming occurs when movements are imagined as well as when movements are actually performed. In other words, these findings can be interpreted as evidence for functional equivalence for response programming of actually performing versus imagining movements. The repetition effect observed in the imagined same force condition can be accounted for by the response programming bypass hypothesis proposed in the previous chapter. That is, the second response was executed on the basis of the motor-program representation formed when the first response was imagined, leading to the bypassing of response programming. In the imagined different force condition, on the other hand, a time-consuming reprogramming operation was needed during the RT to initiate the second response, leading to a longer simple RT. This process was the same as in the control condition.

The present result showed that the size of the repetition effect observed for the actual same force condition was not different from that for the imagined same force condition. A question that arises here is whether actual and imagined movements share common mechanisms in the whole processes of response programming. Roland, Larsen, Lassen, and Skinhoj (1980), who used PET scans technique, found that when movements were actually performed, the supplementary motor cortex and motor cortex were active while, when movements were imagined the supplementary motor cortex, but not the motor cortex, was active. There are some implications that the motor cortex involved in running off the motor program for movements (Deecke, et al., 1969). Therefore, the results of Roland, et al. (1980) may suggest that the shared mechanisms between actual and imagined movements is limited, in that the motor programs can be run off when movements were actually performed, but not when movements were imagined. If this is correct, the view that subliminal neuromuscular activity found during mental practice results from the evocation of motor commands is questionable. Rather, as suggested by Cratty (1973) and Kohl and Roenker (1983), the accompaniment of subliminal neuromuscular activity to imagined movement might be an artifact much like other muscular responses accompanying imagery.

If response programming occurs when movements are imagined, another question that arises is whether response programming precedes imagined as well as actual movements. Jeannerod (1994) suggests that motor imagery and motor preparation are related processes using the same neural substrates. He defines motor preparation as an unconscious process by which a movement is programmed prior to actually being executed. By contrast, he defines motor imagery as a conscious process whereby one can voluntarily evoke a mental image that involves a motor program associated with movement execution independently of any intention to actually perform the movement. In other words, imagining a movement is equivalent to programming the movement. The distinction is based on whether the process is conscious or unconscious. According to this suggestion, response programming may occur not before movements are imagined but between motor imagery initiation and completion. One way to examine the temporal relation between imagined movement and response programming would be to examine whether the amount of blood flow to the supplementary motor cortex increases prior to motor imagery initiation or during motor imagery. There are some implications that the supplementary motor cortex may be involved in the motor preparation (e.g., Brinkman, 1984). Thus, if response programming precedes imagined movement, the amount of blood flow might increase prior to motor imagery initiation. On the other hand, if imagining a movement is equivalent to programming the movement, the amount of blood flow might increase between motor imagery initiation and completion. However, the study of motor imagery with PET scans told us where movements might be programmed, but it could not tell us the temporal relation between imagined movement and response programming. In the present study, within-subject correlations were calculated between the vividness scores for imagery of movement and simple RT to initiate the second response. If imagining a movement is equivalent to programming the movement, the significantly negative correlation might be observed in the imagined same force condition, because more vivid imagery might produce more precise motor program representation, leading to a shorter simple RT. However, the data

did not support this prediction. The mean correlation calculated (-.16) was not significantly different from zero. This finding might suggest that imagining and programming movements do not occur simultaneously.

Mahoney and Avenier (1977) categorized mental imagery into internal imagery and external imagery. Internal imagery is potentially kinesthetic and involves the individual actually approximating the real-life experience in such a way that the person actually feels those sensations that might occur while participating in the real situation. External imagery, on the other hand, is predominantly visual and involves the individual viewing him or herself from the perspective of an external observer. In the present experiment, subjects were asked to use internal imagery. There are some implications that internal imagery enhances motor performance, but external imagery does not (Mahoney & Avenier, 1977). There are also some implications that a combination of visual image and the other sensory images would produce higher levels of performance than mere visual image (Ahsen, 1995). If this is correct, internal imagery might be associated with response programming, but external imagery or visual imagery of movement might be not.

### Experiment 8

Experiment 8 was basically a replication of Experiment 7. Unlike Experiment 7, the interstimulus intervals of 1 and 3 seconds were employed. Experiment 6 showed that the repetition effect vanished when the interstimulus interval is beyond 2 seconds. This result was interpreted to suggest that the motor-program representation of the first response is retained for approximately 2 seconds in a motor output buffer. Thus, if retention time of a motor-program representation is equivalent between actually performing and imagining movements, no repetition effect should be found with the interstimulus interval of 3 seconds for both actual and imagined same force conditions.

### *Method*

*Subjects.* Twenty-four graduate and undergraduate students (16 women and 8 men), ranging in age from 19 to 35 years, with a mean of 22.3 yr., volunteered to serve as subjects. They all wrote with right hands. None had prior knowledge of the hypotheses being tested.

*Apparatus.* The apparatus was the same as in Experiment 1 except that a light stimulus generator (Takei 331) was used to present a red light as a reaction signal. The rise time of the stimulus was approximately 50 msec. Unlike Experiment 1, the EMG apparatus was not used.

*Design.* The design of the experiment was a 2 x 3 (interstimulus interval x response condition) factorial with repeated measures on the last factor. The first factor had two levels, 1-sec. and 3-sec. interstimulus intervals. The second factor was a crossed one of three response conditions. Twelve subjects, 8 women and 4 men, were randomly assigned to each of the 1-sec. and 3-sec. interstimulus interval conditions.

*Procedure.* The procedure was almost the same as in Experiment 7 unless noted otherwise.

Each trial began with a warning tone of 300-msec. duration, followed by a first red light stimulus of 100-msec. duration that occurred with a fixed foreperiod of 1,000 sec. This stimulus served as the signal for subjects to initiate a first response. Following a 1,000-msec. interval for the 1-sec. interstimulus interval condition or a 3-sec. interval for the 3-sec. interstimulus interval condition after the presentation of the first red light, a second red light of 100-msec. duration was presented. This was the signal to initiate a second response.

For each interstimulus interval condition, there were two experimental

conditions: actual force and imagined force. With the actual force condition, the instructed sequence patterns were 30%-30% of the maximum of the isometric grip strength of each subject. Subjects were required to produce the 30% force to both the first and second reaction signals. The procedure for the imagined force condition was the same as in the actual force condition except that subjects were instructed to imagine producing the 30% force to the first reaction signal. In the imagined force condition, subjects were asked to attempt to feel those sensations that might be expected while executing the actual movement (internal imagery). During imagery response, subjects' eyes were opened and subjects held the handles of the dynamometer. Also, subjects were requested not to make any overt movement. In addition, two control conditions were set to examine the net programming time for the second response: short- and long-interval conditions. In both conditions, the first red reaction signal was omitted, and subjects made only one response by producing 30% force following the auditory warning signal. In the short interval condition, the red reaction signal occurred with a fixed foreperiod of 1 sec. for the 1-sec. interstimulus interval condition and 3 sec. for the 3-sec. interstimulus interval condition, respectively. In the long interval condition, however, the red reaction signal occurred with a fixed foreperiod of 2 sec. for the 1-sec. interstimulus interval condition and 4 sec. for the 3-sec. interstimulus interval condition, respectively. This simply meant that there was 1 sec. plus 3 sec. between warning and reaction signals if the interstimulus interval of 3 sec. was used. For the second response, catch trials (by use of go/no-go paradigm) were included at a rate of one-sixth of the trials to discourage subjects from anticipating the reaction signal. On catch trials, a green light of 100-msec. duration was generated, which was the signal not to respond.

Subjects participated in four sessions. The first session provided equal practice for all conditions. In sessions 2 through 4, subjects were randomly assigned to one of the three conditions. Subjects performed 50 blocked trials (30 practice trials and 20 test trials) for each condition. Catch trials were randomly arranged across each condition and subject. The intertrial interval was 10 sec. Each condition was run at 15-min.

intervals. A 1-hr. break was given after the completion of the first three sessions.

The simple RTs below 100 msec. were considered premature reactions and were omitted. All test trials on which premature reaction occurred were repeated at the end of the trial block in which they occurred.

*Dependent measures.* The dependent measures were the same as in Experiment 1 except that simple RT was not separated into premotor time and motor time. These data were analysed via a two-way ANOVA, with the interstimulus interval condition as a between-subjects factor and the response condition as a within-subjects factor. All post hoc analyses were performed using the Newman-Keuls test at the .05 level.

### *Results*

While the original design included two control conditions for each interstimulus interval condition, the data from two conditions were pooled because the main effect of response condition and the interaction of response condition x interstimulus interval were not significant for all dependent measures.

*Force-time measures.* The results of force-time measures on the second response were very similar. ANOVAs showed no main effects for interstimulus interval or for response condition as well as nonsignificant interactions between the two factors, indicating that the second response was the same in terms of force-time patterns across all conditions. Subjects' mean actual peak force for each condition closely matched the expected force, as is indicated by the overall mean actual peak force of 32%. Moreover, all of the responses were quite rapid, as is indicated by the overall mean time to peak force of 108 msec. and mean force duration of 245 msec. In both imagined response conditions, during imagery response, no force was recorded through the electrohandgrip

dynamometer.

Additionally, for both actual response conditions, the force-time measures for the second response were compared with those for the first response. These data were analysed via a two-way ANOVA with two levels of interstimulus interval (1 or 3 sec.) as a between-subject factor and two levels of serial position (first or second) as a within-subjects factor. ANOVAs showed no main effects of interstimulus interval and of serial position as well as nonsignificant interactions between the two factors, indicating that the second response was the same in terms of force-time patterns across all conditions. These findings indicate that subjects were able to meet the task constraints imposed by the experimenter. The mean maximal isometric grip strength (with standard deviations) for the right hand were 39.4 kg (8.18) and 41.2 kg (10.02) for the 1-sec. and 3-sec. interstimulus-interval conditions, respectively, which were not significantly different from each other.

*Simple RT.* The Figure 9 shows mean simple RT as a function of interstimulus interval condition and response condition for the second response. The ANOVA indicated significant main effects of interstimulus interval ( $F(1, 22) = 17.31, p < .01$ ) and of response condition ( $F(2, 44) = 6.39, p < .01$ ). The interaction between the two factors approached significance ( $F(2, 44) = 2.61, .05 < p < .10$ ). Analysis of interaction showed that the 3-sec. condition produced significantly longer simple RT than did the 1-sec. condition across all response conditions ( $ps < .05$ ), indicating the well-known effects of prolonging the duration of the foreperiod (e.g., Karlin, 1959). More important, there were no different simple RTs among the response conditions for the 3-sec. condition, whereas there were significant differences in simple RTs among the conditions for the 1-sec. condition ( $F(2, 44) = 8.57, p < .01$ ). Post hoc analysis showed that the actual response and imagined response conditions produced shorter simple RTs than did the control condition. However, there was no significant difference in simple RT between the actual response and imagined response conditions. With the first

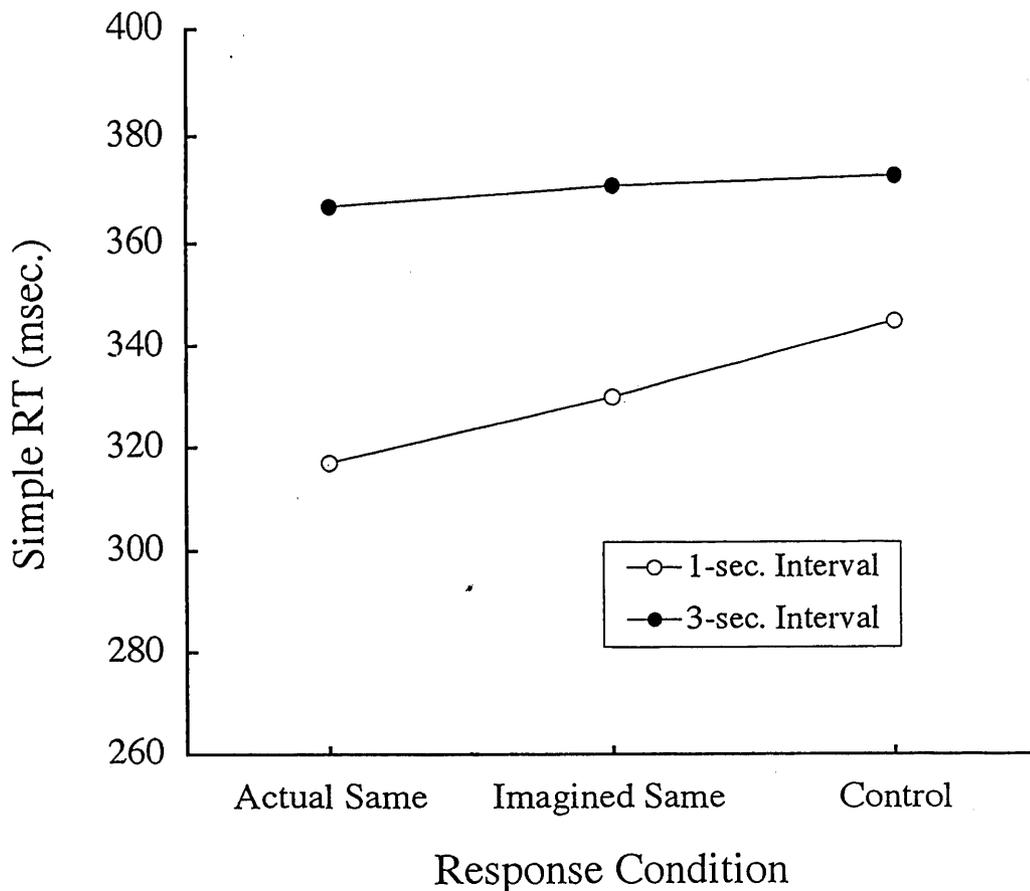


Figure 9. Mean simple reaction time (RT) in Experiment 8 as a function of interstimulus interval condition and response condition for the second response.

response, the mean simple RTs were 238 and 247 msec. for the actual same force condition and the imagined same force, respectively, which were not significantly different from each other. The first response produced shorter RT than did the second response, which is no surprise because the first response did not include catch trials.

*Errors.* Premature reactions were extremely infrequent, and the over-all mean error rate was less than 0.1%. However, the catch-trial errors were produced at a high rate, as indicated by the overall mean rate of 23.6%, but evenly distributed across all conditions. The analyses indicated no main effect of interstimulus interval or of response condition, nor was there an interaction between the two factors.

### *Discussion*

Consistent with the result of Experiment 7, repetition effects were observed for both the actual and imagined same force conditions when the interstimulus interval was at 1 second. As hypothesized, moreover, the repetition effect completely vanished when the interstimulus interval was at 3 seconds. Again, these findings support the view of functional equivalence for response programming of actually performing versus imagining movements.

There is accumulating evidence to indicate that mental practice is effective in the improvement of motor skills (Féltz & Landers, 1983). The present evidence that response programming occurs during imagined movement may give some insight into why mental practice is effective in improving performance of motor skills. According to the Schmidt's (1975) schema theory, a fundamental aspect of the learning of motor skills involves the acquisition of rules that structure the relationship between the production and evaluation of motor responses. One such rule is termed the recall schema, which is comprised of the relationship between response specifications (parameters) required to execute the motor program and actual outcomes (as modified by initial conditions). In this case, given that response programming occurs during imagined movement, it is reasonable to think that subjects can select the parameters issued to the motor program even when movements are mentally practiced. On the other hand, while mental practice cannot generate the information about actual outcomes, subjective movement evaluation can be substituted for actual outcome information (Schmidt, 1975). From this point of view, mental practice can be seen as developing a recall schema that can be used to effectively learn a motor skill. Needless to say, however, mental practice is much less effective in the improvement of motor skills than actual practice. It is so because subjective movement evaluation is inferior to actual outcome information in correctness, thus mental practice cannot establish recall schema so strong as actual practice can.

## Conclusion

Two experiments in this chapter are conducted to clarify the functional equivalence for response programming of actually performing versus imagining movements, by showing that the repetition effect that stems from response programming occurs when responses are imagined as well as when responses are actually performed. For this purpose, the simple RT to initiate the second of two serial responses was examined when the first response is covertly performed, but the second response is actually performed.

In Experiment 7, subjects were required to produce the sequence of same or different force after the two reaction signals separated by the interstimulus interval of 1 second. Simple RTs to initiate the second response were significantly shorter for imagining and actually performing the same force responses than for imagining and actually performing different force responses or the control condition. These findings suggested that the repetition effect occurs when responses are imagined as well as when responses are actually performed.

Experiment 8 was basically a replication of Experiment 7 except that the interstimulus intervals of 1 and 3 seconds were employed. Repetition effects were observed for both the actual and imagined same force conditions when the interstimulus interval was at 1 second, but completely vanished when the interstimulus interval was at 3 seconds. This result suggested that the repetition effect that arises from imagined response may be retained within the first 2 seconds.

The findings of Chapter 5 were interpreted as evidence for functional equivalence for response programming of actually performing versus imagining movements.

## CHAPTER 6

### SUMMARY AND CONCLUSIONS

Typically, when subjects are required repeatedly to execute the quick and correct responses for stimuli that are presented in rapid succession, the RT for a repeated stimulus is shorter than for a nonrepeated stimulus (Bertelson, 1961, 1963). This phenomenon, termed the *repetition effect*, suggests that when the same stimulus is repeated, some aspects of the information processing between stimulus and response proceed more quickly. Although several investigators have attempted to identify the stage or locus of the processing facilitated by repetition, the most important contribution to an understanding of the locus of the effect comes from the study done by Pashler and Baylis (1991b).

Pashler and Baylis (1991b) proposed five possible loci of the repetition effect based on the stage model of the information processing and tested these alternative hypotheses by using an information-reduction procedure. In this procedure, multiple stimuli were mapped to each response, so that the same stimulus and response were repeated on successive trials (stimulus repetition) or the same response was repeated without repeating the same stimulus (response repetition). These conditions were compared with the condition in which neither stimulus nor response was repeated, thus, no repetition effect was expected (nonrepetition).

The first two hypotheses were related to the stage of stimulus identification. First, the repetition effect may originate in perceptual processing between percept and stimulus identification. This predicts that the effect is observed only for stimulus repetition, regardless of categorizability of the stimuli. Second, the effect may originate

in the process of stimulus categorization. This predicts that the effect is found for both stimulus and response repetitions when the stimuli used are categorizable. Two further hypotheses were related to the stage of response selection. One possibility is that the effect may arise from the process of response selection between stimulus identification and response. It predicts that the effect is observed only for stimulus repetition, regardless of categorizability of the stimuli. Another is that the effect may arise from the process of response categorization. This predicts that the effect is found for both stimulus and response repetitions when the stimuli are categorizable. Finally, the effect may originate in response execution. This predicts that the effect is observed for both stimulus and response repetitions, regardless of categorizability of the stimuli.

Pashler and Baylis (1991b) found a remarkable repetition effect only for stimulus repetition, regardless of categorizability of the stimuli, suggesting that the repetition effect may be localized in either perceptual processing or response selection. To test these possibilities, they examined what happens when the same stimulus is repeated on successive trials, but with different responses to be selected. If the repetition effect originates in perceptual processing, the effect should persist. If the repetition effect originates in response selection, on the other hand, a change in the response modality should abolish the effect. The repetition effect was completely abolished. Consequently, Pashler and Baylis (1991b) concluded that the repetition effect occurs only when the same stimulus and the same response are repeated and that the effect is localized in the stage of response selection.

There is, however, another central process associated with the preparation of response, which occurs after response selection and precedes the execution of motor response. This process is commonly referred to as *response programming* (e.g., Klapp, 1995; Schmidt & Lee, 1999). Response programming is defined as more detailed specification of the response code that was established during response selection, and its resultant representation is referred to as the *motor program* (e.g., Keele, 1986; Klapp, 1996; Rosenbaum, 1991; Sanders, 1998; Zelaznik & Hahn, 1985). Despite a great deal

of evidence for response programming and motor program, no research has investigated whether or not the repetition effect is related to response-programming stage. Therefore, the present study was conducted to examine the involvement of response programming in the repetition effect. The way that was used to accomplish this goal was by examining what happens on the RT to initiate the second response when two successive responses are the same or different in their force-time characteristics, or more specifically, when they are the same or different in their motor programs. The task used was an isometric force-production task. Subjects were required to react and produce the sequence of the same or different force by squeezing the handle as quickly and accurately as possible for each of the first and second reaction signals that are presented in rapid succession. It was assumed that the repetition effect occurs only when the same force response is repeated on successive responses, because the motor program for the preceding response could be reused for the next response.

In Chapter 3, the possibility that the repetition effect occurs at the stage of response programming was examined using Pashler and Baylis's (1991b) information-reduction procedure. Experiment 1 as a preliminary experiment examined whether varying force magnitude influences the RTs in both simple and choice RT paradigms. The RT to initiate force response did not change across the range of forces examined in both simple and choice RT conditions, regardless of whether a desired force was selected by the experimenter or by the subject. These findings suggested that the time required to program force response is invariant across the range of forces examined. Experiment 2 examined the effect of the similarity of serial force responses on repetitions with a noncategorizable mapping in a choice RT paradigm. Experiment 3 examined the effect of the similarity of serial responses on repetitions with a categorizable mapping in a choice RT paradigm. Consistent with the results reported by Pashler and Baylis (1991b), both experiments showed repetition effects only for stimulus repetition when the different response or free response was repeated on successive responses, regardless of categorizability of the stimuli. These findings

supported the response-selection hypothesis of the repetition effect. When the same force response was repeated, however, repetition effects were observed not only for stimulus repetition but also for nonrepetition. These findings were interpreted as evidence for two loci of the repetition effect: response selection and response programming. Finally, Experiment 4 examined the effect of the similarity of serial responses on repetition effects in a simple RT paradigm. When the same force response was repeated on successive responses, repetition effects were found for all of the stimulus repetition, response repetition, and nonrepetition. When the different force response was repeated, on the contrary, repetition effects vanished completely across all the repetition conditions. Thus, the results of Experiment 4 suggested that when the same responses are repeated under the simple RT condition, response programming is the primary locus of the repetition effect.

In conclusion, experiments in Chapter 3 suggested that if the same response is repeated on successive responses, in a serial choice-RT situation, repetition effects originates in both response selection and response programming, whereas in a serial simple-RT situation, response programming is the primary locus of the repetition effect.

Experiment 5 in Chapter 4 addressed a question of whether the repetition effect observed in simple RT situation is due to a speedup or bypassing of the processing of the response programming. To test these alternative hypotheses, a psychological refractoriness paradigm was adopted (for reviews, see Sanders, 1998; Smith, 1967; Welford, 1980). In this paradigm, two stimuli are presented in rapid succession, but unlike in a repetition effect paradigm, the second stimulus is usually presented before the initiation or during the execution, of the first response. The typical finding is that the RT to the second of the two stimuli is considerably delayed, compared with the control RT when it is presented alone. Single-channel theories propose that somewhere in the central processing stages there is a bottleneck that cannot process more than one task at a time. When the processing stage is occupied with a first task, processing a second task must be postponed until the stage becomes available. Thus, the RT to the second

stimulus is delayed. There is evidence suggesting that under the simple RT circumstances, the bottleneck is at the response-programming stage (e.g., Davis, 1957, 1959; Karlin & Kestenbaum, 1968; Kroll, 1961). Thus, one way to test the present alternative hypotheses by using this paradigm is to observe what happens on the simple RT when the similarity of serial responses is manipulated. One plausible prediction is that when the different force response is repeated on successive responses, a typical refractoriness effect would be observed. When the same force response is repeated on successive responses, on the other hand, the response programming speedup hypothesis predicts that the refractoriness effect would still be observed, but the size of the effect should be smaller than for the different force condition. The response programming bypass hypothesis predicts that the refractoriness effect should vanish and instead the repetition effect may be observed. The results clearly supported the response programming bypass hypothesis that the repetition effect that originates in response programming is due to bypassing of the normal response programming. This bypassing was explained in terms of direct access to the motor-program representation in the motor output buffer.

Experiment 6 in Chapter 4 addressed a question of how long the repetition effect that arises from response programming is retained, or more specifically, how long a constructed motor program is retained in the motor program output buffer. One way to examine this is to observe the effects of variations in interval between the first and second responses on simple RT to initiate the second response when the same force response is repeated on successive responses. In this case, it is expected that the simple RT to initiate the second response would be nearly maximized at the retention interval at which the repetition effect vanishes. The result showed that the simple RT to initiate the second response increased sharply as the length of the retention interval increased from 0 to 2 seconds, with no further increases thereafter. These findings were interpreted as suggesting that the repetition effect that arises from response programming may be retained within the first 2 seconds, which may be the approximate

upper limit for the retention of the constructed motor program.

Chapter 5 examined whether the repetition effect that stems from response programming occurs when responses are imagined as well as when responses are actually performed. For this purpose, the simple RT to initiate the second of two serial responses was examined when the first response is covertly performed, but the second response is actually performed. In Experiment 7, subjects were required to produce the sequence of same or different force after the two reaction signals separated by the interstimulus interval of 1 second. Simple RTs to initiate the second response were significantly shorter for imagining and actually performing the same force responses than for imagining and actually performing different force responses or the control condition. These findings suggested that the repetition effect occurs when responses are imagined as well as when responses are actually performed. Experiment 8 was basically a replication of Experiment 7 except that the interstimulus intervals of 1 and 3 seconds were employed. Repetition effects were observed for both the actual and imagined same force conditions when the interstimulus interval was at 1 second, but completely vanished when the interstimulus interval was at 3 seconds. This result suggested that the repetition effect that arises from imagined response is retained within the first 2 seconds. The findings of Chapter 5 were interpreted as evidence for functional equivalence for response programming of actually performing versus imagining movements.

Understanding the mechanism underlying repetition effect has important practical and theoretical implications. On the practical side, for example, if physical educators and coaches want to know how goal-directed movements are achieved in a game situation, they should place the focus of the game analysis not only on the movement at one moment in time but also on sequenced movements that are executed in a context. This is because the repetition effects certainly appear in a constantly changing game situation. An understanding of the mechanism of repetition effect may also be useful in the rational design of working environment that requires fast and correct responses. For example, as suggested by the present study, the stimulus-response

mapping should be by assigning each stimulus to a unique response, but not by assigning more than one stimulus to the same response. The latter arrangement by many-to-one mapping will result in delayed and erroneous responses. On the theoretical side, an understanding of the mechanism underlying the repetition effect may provide insights into the nature and control of mental processes underlying many human motor skills. For example, if motor learning is regarded as the accumulation of repetition effect, identifying the processes of the information processing facilitated by repetitions may provide a new avenue for developing models of the changes that underlie motor learning. The present fact that the processes of response selection and response programming are highly sensitive to repetitions may strongly suggest the involvement of these processes in the changes of motor learning. The present study also clarified the functional equivalence for response programming of actually performing versus imagining movements, by showing that the repetition effect that stems from response programming occurs when response is imagined as well as when response is actually performed. This evidence may provide some insights into why mental practice is effective in improving motor skills.

By exploring the old, one becomes able to understand the new. Future research efforts should be directed towards pursuing these possibilities that the repetition effect implies.

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