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1988

The response switching effect.

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THE RESPONSE SWITCHING EFFECT

A Thesis Presented

by

HEATHER J. BARNES

Submitted to the Graduate School of the
University of Massachusetts in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

February 1988

Psychology

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ACKNOWLEDGEMENTS

I wish to thank Dr. David Rosenbaum for his guidance and support throughout this project. To Dr. Keith Rayner, Dr. Jerome Myers, and Dr. Michael Jordan, I am grateful for their guidance and encouragement. The expectations of the entire committee were certainly motivators for my efforts. I wish to acknowledge Dr. Jonathan Vaughan for his suggestions in the final stages of the project.

I wish to express my deepest appreciation to my husband, Glenn Barnes, his encouragement and support will always be treasured throughout my academic endeavors.

ABSTRACT

THE RESPONSE SWITCHING EFFECT

FEBRUARY 1988

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The response switching effect refers to the finding that when one alternates between saying the syllable "ba" and tapping the right index finger, the overall production rate is slower than when the "ba" is repeatedly said and the index finger is repeatedly tapped. Experiment 1 was conducted to verify the response switching effect through formal, systematic experimentation. Analyses of variance were conducted on response rate, initiation time interresponse time and error. The results of Experiment 1 verified the response switching effect. Experiments 2 was conducted in order to examine the possibility of a fundamental inability to switch quickly from one response modality to another. Analyses conducted on and examination of response rate, initiation time interresponse time and error ruled out the possibility that the effect is caused by a fundamental inability to switch quickly between response modalities. Experiment 3 was conducted to in order to determine the effect of structural differences and the effect of production time differences as possible causes of the response switching effect.

Experiment 3 also examined the generality of the response switching effect by extending the effect to a task that involved the alternation of manual and pedal responses. The results suggested that structural differences and production time differences are in part causes of the response switching effect. Further, because the effects of structure and the effects of time relation did not interact in any of the dependent measures, structural differences and production time differences appear to affect different aspects of the execution of alternating manual and pedal responses. The central clock model and related phenomenon were discussed in relation to the response switching effect.

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CHAPTER 1

INTRODUCTION

The literature is full of examples of the motor system utilizing parallel production (Gentner, 1982; Gentner, Grudin, and Conway, 1980; Kent & Moll, 1972). Parallel production consists of executing two or more movements simultaneously. This results in increased prooduction rates when alternating responses. Serial production differs in that movements must be executed sequentially. Thus, the execution of a response cannot begin until the completion of the prevuos response. The effects of parallel production are so robust that one can observe the increased response rates outside the laboratory. While tapping the right index finger as quickly as possible, note the production rate. While alternating the right and left index finger as quickly and as accurately as possible, note that the overall production rate is much faster than the production rate of tapping the right index finger alone. A similar result is found by repeatedly saying the syllable "ba" and alternating saying the syllables "ba" and "da".

The motor system can utilize parallel production during manual tasks such as typing (Gentner, 1982; Gentner, Grudin, & Conway, 1980; Rumelhart & Norman, 1982). Gentner (1982) revealed this point by considering various kinds of letter transitions. A digraph typed with one finger of the same hand, such as *ce*, is referred to as a one finger digraph (1F), a digraph typed with two fingers from the same hand, such as *ta*, is referred to as a two finger digraph (2F), and a digraph typed with two fingers from different hands, such as *th*, is referred to as a two hand digraph (2H). Gentner reported that the interstroke interval of the digraph when typed by experienced typists varied as a function of the digraph type. According to Gentner, the interstroke interval of the 1F digraph is slowed because the finger cannot begin moving to the next target key until it completes the previous keypress. The interstroke interval of the 2F digraph is faster than that of the 1F digraph because one finger can move while the other is typing. However, because the two fingers are of the same hand, the hand constrains the movement. The interstroke interval of the 2H digraph is faster than that of both the 1F and 2F digraphs because of the greater biomechanical independence of the two hands. Gentner, Grudin, and Conway (1980) presented cinematic evidence for this explanation of the differences in digraph speed.

Keele (1986) discussed a report by Langfeld (1915) where subjects displayed parallel production during a finger tapping task. Subjects were instructed to tap the right index finger as quickly as possible, to tap the right middle finger as quickly as possible, and to alternate the right index and middle fingers in an out-of-phase (one finger extending while the other is extending) mode as quickly as possible. While the rate of each finger was actually slower than the rate of when the respective fingers tapped alone, the alternating rate was 30% faster than the single tapping rates. Thus, the motor system utilizes parallel production during manual tasks.

The vocal system also displays parallel production during speech. Hudgins and Stetson (1937), as reported in Lenneberg (1967), found that the "relative speed of articulatory movements" (p.115) ranged from 7.5 per second in the case of repeatedly saying "pa-ta" to 5.5

for repeatedly alternating between "pa-pa". The explanation for this difference is that when repeating the same syllable, the vocal musculature cannot begin uttering the next syllable until it completes the syllable it is uttering. However, when alternating between syllables which differ in respect to the musculature that produces each syllable, the vocal musculature can prepare to say the next syllable before completing the syllable it is uttering. This is analogous to Gentner's (1982) explanation of the differences between the interstroke intervals of 1F, 2F, and 2H digraphs.

Further evidence of parallel production in the vocal system is provided by examples of coarticulation. Kent & Moll (1972) provided evidence for parallel production during speech through cinefluorographic tracings. Kent & Moll found similar trajectories and velocities of the tongue moving from /i/ to /a/ in "he monitored" and "he honored" even though in one of these cases the vowels are separated by a bilabial consonant. Kent, Carney & Severeid (1974) claimed that motor programs are executed simultaneously for more than one articulator. Examples are seen in the production of words such as *contract* and *camping*. In *contract*, velar elevation begins with lip movements for alveolar closure. In *camping*, velar elevation begins with lip movements for bilabial closure. In these examples the simultaneous execution of the articulators were for the same phonetic segment; however, simultaneous execution of articulators are not always for the same phonetic segment. Sometimes an articulator is prepared for execution three or four phonemes before it is actually executed. Kent et. al. claimed that simultaneous executions are evidence that motor programs can be initiated in parallel. Each of these examples provides evidence for parallel production during speech production.

In view of the fact that both the manual and the vocal systems are capable of using parallel production, the execution of alternating vocal and manual responses should be faster than repeating vocal and manual responses if parallel production takes place. Informal experimentation that I conducted, in collaboration with D. Rosenbaum and J. Reider, suggested that alternating between vocal and manual responses was slower than repeating a manual response or repeating a vocal response. We used the term response switching effect to refer to the phenomenon that the overall production rate associated with alternating between a vocal and a manual response is slower than the rate of the vocal response repeated alone and the rate of the manual response repeated alone. More specifically, the response switching effect refers to the finding that when one alternates between saying the syllable "ba" and tapping the right index finger, the overall production rate is slower than when the "ba" is repeatedly said and the index finger is repeatedly tapped. Experiment 1 was conducted to verify the response switching effect through formal, systematic experimentation. Experiments 2 and 3 were conducted to evaluate alternative models of the effect.

CHAPTER 2

EXPERIMENT 1

Method

Subjects. Six right handed Hampshire College students participated in this experiment. Each subject was paid an hourly wage plus bonuses.

Apparatus. The subject sat in a private testing room facing a video screen. A Shure 5755 microphone that triggered a Gerbrands G1341 voice key was placed in front of the subject, and a telegraph key was positioned off center toward the subject's right side. The experiment was controlled by an Apple II computer equipped with a Cognitive Testing Station (Digitry Corporation, Medford, Ma).

Procedure. The task was to perform rapid vocal and manual responses. The vocal response was saying the syllable "ba." The manual response consisted of tapping the telegraph key with the right index finger. The four conditions included a pure vocal condition consisting of repeating the syllable "ba" as quickly as possible, a pure manual condition consisting of repeatedly tapping the right index finger as quickly as possible, a mixed vocal-manual condition consisting of repeatedly alternating between the vocal and the manual responses as quickly as possible, beginning with the vocal response, and a mixed manual-vocal condition consisting of repeatedly alternating between the manual and the vocal responses as quickly as possible, beginning with the manual response.

The experimenter read instructions that explained each condition and the experimental procedure. Following this explanation, the subject practiced each of the conditions. At the beginning of each block, the subject was told which condition he/she should perform. A block consisted of 10 trials, and a trial consisted of six renditions of the required condition. A rendition was defined as a requisite pair of responses (e.g., "ba"-tap in the vocal-manual condition). On a given trial, a warning signal (a 5.5 cm X 4.5 cm rectangle) appeared on the screen. Following a variable foreperiod ranging from 400 *ms* to 1000 *ms*, the warning signal disappeared and the imperative signal, an asterisk, appeared in the center of the rectangle. The imperative signal remained on the screen until the subject completed the requisite number of responses. Since there was no penalty for performing extra renditions, the subject did not have to count the number of renditions he/she performed. Subjects performed three consecutive blocks of each condition. The order of the conditions was counterbalanced across subjects. At the end of each trial, the subject received feedback. If the subject completed four or more correct renditions, the feedback included the mean interresponse time, the number of correct renditions, and a prompt which said, "Try to go faster." Alternatively, if the subject completed less than four correct renditions, the feedback included the number of correct renditions and a prompt which said, "Try to be more accurate."

In order to reduce the use of auditory feedback, the subject wore headphones with white noise [-15 dB] from a noise generator. A testing session lasted approximately 30 minutes.

Results and Discussion

Response Rates. An ANOVA evaluating the effects of first response (vocal, manual) x structure of the second response (same as the first response, different from the first response) was conducted on the mean response rate. Response rates were averaged across renditions two through six. The first rendition was excluded from the analysis because the increased initiation time would decrease the rate. The mean response rates as a function of condition are presented in Table 1 (see page 8). The main effect of first response was significant, $F(1, 5) = 7.83$, $p < .03$; the mean rate of conditions beginning with a vocal response was 5.38 responses per second (res/sec), and the mean rate of conditions beginning with a manual response was 7.44 res/sec. The main effect of structure was significant, $F(1, 5) = 25.75$, $p < .003$; the mean rate of the pure conditions was 7.25 res/sec, and the mean rate of the mixed conditions was 5.56 res/sec. Thus, support for the response switching effect is provided by the result that the response rate was faster in the pure conditions than in the mixed conditions.

<u>Initiation Time.</u> Table 2 (see page 9) presents the mean latencies of initial and noninitial responses as a function of condition. An ANOVA evaluating the effects of condition (vocal-vocal, manual-manual, vocal-manual, manual-vocal) x block (1, 2, 3) was conducted on the mean initiation times (T_1). The main effect of condition was significant, $F(3,15) = 6.731$, $p < .004$; mean initiation times as a function of condition were vocal/vocal 358 *ms*, manual/manual 300 *ms*, vocal/manual 430 *ms*, and manual/vocal 341 *ms*. The condition x block interaction was significant, $F(6,30) = 3.208$, $p < .01$. Figure 1 (see page 10) illustrates this interaction. As the number of blocks increased from one to three, T_1 of the vocal-vocal condition decreased from 406 *ms* to 311 *ms*. However, T_1 was

Table 1

Mean production rate (responses/second) as a function of condition in Experiment 1.

Condition	Production Rate
Vocal/Vocal	6.02
Manual/Manual	8.48
Vocal/Manual	4.73
Manual/Vocal	6.40

Table 2

Mean latencies of initial and noninitial responses as a function of condition in Experiment 1.

Condition	Initial Response	Noninitial Couplet Position 1	Noninitial Couplet Position 2	Noninitial Mean
Vocal/ Vocal	358	152	153	153
Manual/ Manual	300	124	121	123
Vocal/ Manual	430	253	170	212
Manual/ Vocal	341	157	193	175

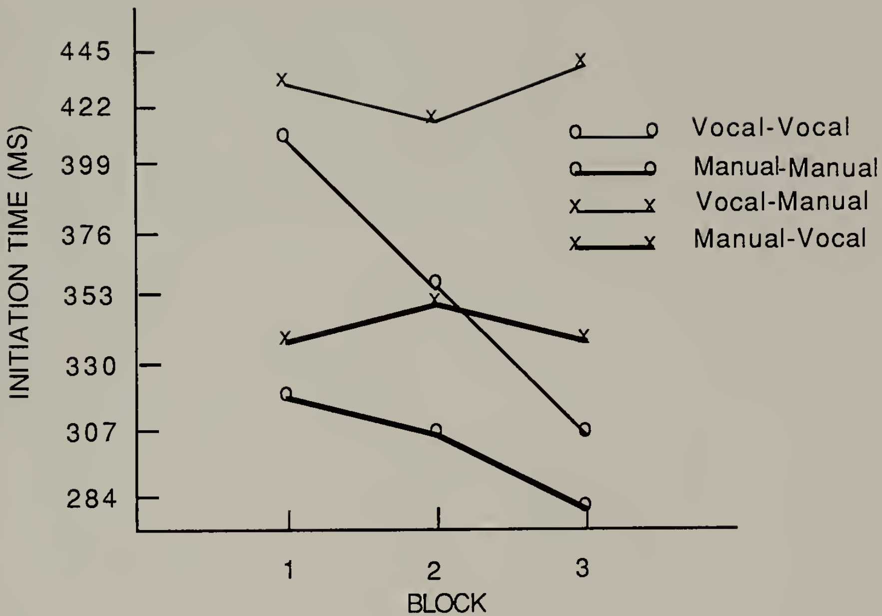

Figure 1. Initiation time as a function of condition and block in Experiment 1.

relatively stable for the other conditions: T_1 of the manual-manual condition decreased from 314 *ms* to 284 *ms*, T_1 of the vocal-manual condition decreased and then increased from 433 *ms* to 438 *ms*, and T_1 of the manual-vocal condition increased and then returned to 337 *ms*. Thus, T_1 for the pure conditions decreased with practice, but T_1 for the mixed conditions did not.

Interresponse Time. Whereas the analysis of response rate gives a general summary of the speed of performance, I also wanted to examine local timing changes. The mose natural measure for this purpose is the interresponse time, which is simple the reciprocal of rate. An ANOVA that evaluated the effects of condition (vocal-vocal, manual-manual, vocal-manual, and manual-vocal) x block (1, 2, 3) x rendition (2, 3, 4, 5, 6) x couplet position (1, 2) was conducted on the interresponse time data. The first rendition was excluded from the analysis because the initiation response would have resulted in rendition interactions because the initiation time was much longer than the interresponse times. For trials in which errors occurred, only those renditions occurring before the errors were included in the analysis.

Table 3 (see page 12) presents the interresponse times of each condition as a function of the block. The main effect of condition, $F(3,12) = 7.47$, $p < .004$ was significant, as was the main effect of block, $F(2,8) = 8.471$, $p < .01$, and the main effect of rendition, $F(4,16) = 18.00$, $p < .001$; the mean interresponse time for each rendition increased from 158 *ms* to 171 *ms* as the number of renditions increased from two to six. The main effect of response was significant, $F(1,4) = 7.04$, $p < .05$; the mean interresponse time

Table 3

Interresponse time as a function of condition and block in Experiment 1.

Condition	Block			Mean
	1	2	3	
Vocal/Vocal	152/149	148/161	156/148	152/153
Manual/Manual	125/120	122/123	123/120	124/121
Vocal/Manual	259/174	260/163	251/165	253/120
Manual/Vocal	188/121	158/197	124/170	172/159

for the first response was slower (172 *ms*) than the second response (59 *ms*).

The condition x couplet position interaction was significant, $F(3,12) = 13.00$, $p < .001$; interresponse times for the pure conditions remained the same across responses one and two, but interresponse times for the alternating conditions changed as a function of the output mechanism. Further, examining the vocal interresponse times as a function of condition and couplet position, the vocal response in the first couplet position was 101 *ms* slower in the mixed condition than in the pure condition and the vocal response in the second couplet position was 40 *ms* slower in the mixed condition than in the pure condition. Examining the manual interresponse times as a function of condition and response within rendition, the manual response in the first couplet position was 33 *ms* slower in the pure condition than in the mixed condition. The manual response in the second couplet position was 16 *ms* slower in the pure condition than in the mixed condition.

The three-way interaction was significant, $F(12,48) = 4.61$, $p < .001$. Interresponse times within the pure conditions remained relatively constant across and within the renditions. However, the interresponse times within the alternating conditions differed as a function of the output mechanism of the corresponding responses. The three-way interaction showed that within response one or two, interresponse times in the manual-vocal condition remained relatively stable: as the number of renditions increased from two to six, the response one (manual response) interresponse times were 158 *ms*, 161 *ms*, 151 *ms*, 153 *ms*, and 163 *ms* respectively, and the response two (vocal response) interresponse times were 180 *ms*, 191 *ms*, 201 *ms*, 196 *ms*, and 195 *ms* respectively. The interresponse times in the vocal-manual condition were not as stable: as the number of renditions increased within response one (vocal responses), the interresponse times were 262 *ms*, 267 *ms*, 257 *ms*, 233 *ms*, and 247 *ms*, and within response two (manual responses) they were 135 *ms*, 153 *ms*, 172 *ms*, 189 *ms*, and 203 *ms* respectively.

Note that the response switching effect is best revealed in the condition x couplet position interaction. The interresponse times of mixed condition responses in both couplet positions are slower than their respective interresponse times in the pure conditions.

Errors. An ANOVA performed on the percentage of correct responses evaluated the effects of condition (vocal-vocal, manual-manual, vocal-manual, manual-vocal) x block (1, 2, 3) x rendition (1, 2, 3, 4, 5, 6). The percentage of correct responses is defined as the number of correct responses in a trial divided by the total number of possible responses. Once an error was made the remaining responses to the end of the trial were categorized as errors in their respective renditions because each of these responses fell in the incorrect serial position. The main effect of condition was significant, $F(3,15) = 10.84$, $p < .001$; the percentage of correct responses was .98 for the vocal-vocal condition, .96 for the manual-manual condition, .85 for the manual-vocal condition, and .67 for the vocal-manual condition. The main effect of rendition was also significant, $F(5,25) = 56.21$, $p < .001$; accuracy decreased as the number of renditions increased. The two way interaction, condition x rendition, was significant, $F(15,75) = 7.49$, $p < .001$. Accuracy of the manual-manual condition ranged from .98 to .96, accuracy of the vocal-vocal condition ranged from .99 to .94, accuracy of the manual-vocal condition ranged from .94 to .71, and accuracy of the vocal-manual condition ranged from .91 to .52.

Overall, the vocal-manual condition was more susceptible to error than the manual-vocal condition. The vocal-manual condition was associated with a greater number of errors and a significant decrease in accuracy occurred earlier than with the manual-vocal condition.

CHAPTER 3

EXPERIMENT 2

The results of Experiment verify the response switching effect through formal, systematic experimentation. What is the cause of the effect? One possibility is that there is a fundamental inability to quickly switch from one response modality to another. Two areas of research provide relevant background for discussing this possibility. One concerns serial versus parallel production of simultaneous vocal and manual response and other is the cerebral space model.

Hollender (1980) addressed the issue of serial and parallel production of simultaneous vocal and manual responses in a series of three experiments. He hypothesized that simultaneous letter naming and key pressing to letter stimuli is possible without interference. When the tasks were performed singly (pure conditions), the naming reaction time (RT) was faster than the key pressing RT, but during a simultaneous naming and key pressing task (mixed condition), the naming RT was significantly slower than the key pressing RT. The key pressing RT remained unchanged in the pure and mixed conditions. Hollender provided two interpretations of these results. One was that some stage or stages of stimulus identification and response preparation for the two tasks could not be processed in parallel. The other was that the systems coupled in the mixed condition. Because of limit capacity for processing the vocal and the manual response are processed as a couplet pair of responses.

The second experiment reported by Hollender (1980) tested these alternative explanations. This experiment used three groups. One group performed the three conditions tested in Experiment 1 and replicated the results of the first experiment. The results from a second group, who named the letter, pressed the appropriate key, and were instructed to synchronize the two responses, were similar to those of the first group. In the pure conditions the naming RT was faster than the keypressing RT. When the mixed condition called for the subjects to synchronize the two responses, the naming RT was slower than the key pressing RT. A third group named the letter, pressed the appropriate key, and was instructed to give priority to the vocal response during simultaneous naming and key pressing responding. The results indicated that during the simultaneous task, the naming responses were faster than the key pressing responses. However, the naming responses were much slower during the synchronization condition compared to the pure condition. Thus, the results from each of the three groups replicated the finding of Experiment 1.

The purpose of Hollender's third experiment was to examine synchronization performance without RT pressures. Subjects were instructed to synchronize the naming and key pressing responses any time after the stimulus appeared. The results indicated that RT pressure was not the cause of the slowed naming response during the synchronization condition. The naming response was slower compared to the key pressing response during the synchronization task. Hollender did not address this issue, but perhaps subjects were trying to synchronize feedback arrival times of vocal and manual responses. If the manual feedback time is longer, the vocal RT would have to be delayed. This is in agreement with Paillard's (1946) report that when subjects try to produce simultaneous responses from differing response systems, they produce the response with the longer efferent time first by an amount plausibly attributed to the afferent time difference. In concluding, Hollender suggested that the naming and key pressing responses are grouped in the mixed conditions. This grouping calls for the slowing of the naming response in order for it to be coupled with the slower key pressing response. The fact that in Experiment 2 subjects were unable to give priority to naming in the mixed condition as compared to naming times in the pure condition indicates that the two systems do not couple for the mere purpose of performing the task goal. Instead, Hollender claimed that the coupling occurred as a result of limited processing capacity. However, this coupling may change as a result of the task.

The functional cerebral space model also provides relevant background for explaining the results of simultaneous vocal and manual responding. Kinsbourne and Hicks (1978) proposed a physiological explanation for the control of simultaneous vocal and manual tasks. They suggested that the greater the functional distance separating neural control areas responsible for generating motor programs, the smaller the interference during simultaneous performance of the tasks that use those programs. Speech of a right handed person is primarily controlled through the left hemisphere of the brain. Similarly, the left hemisphere controls manual tasks performed with the right hand. According to the functional cerebral space model, right handed subjects should show performance decrements during simultaneous right handed manual and vocal tasks, but not during simultaneous left handed manual and vocal tasks. Further, because speech of left handed people is not always controlled through the left hemisphere, performance decrements during simultaneous vocal and manual tasks should not be as prominent.

Hicks (1975) provided evidence supporting these hypotheses. He reported that right handed subjects (with no left handed relatives) who were practiced at left and right index finger dowel rod balancing had shorter right handed balancing times during a simultaneous vocal task. Left handed balancing times were unchanged when the vocal task was performed simultaneously. When the phonetic difficulty of the vocal task (repeating sentence), was increased, right handed balancing times decreased more compared to the easier phonetic vocal task. This effect was seen in all subjects but to a greater degree in the right handed subjects (with no left handed relatives). Further, vocal errors occurred more during right handed balancing compared to left handed balancing. Hicks reported that the balancing times of left handed subjects were not affected by the vocal tasks. Also, right handed subjects with left handed relatives showed variable results.

Kinsbourne and Cook (1971) also found support for a functional cerebral distance model in an experiment consisting of simultaneous dowel rod balancing and speaking and an experiment consisting of simultaneous dowel rod balancing and a silent rehearsal task. In both experiments shorter balancing times were associated with right handed balancing compared to left handed balancing when the vocal tasks were performed simultaneously.

Briggs (1975) reported an experiment with similar results. During a practiced bimanual motor task, the total number of errors made by right handed subjects did not increase with the concurrent vocal task. However, during the concurrent vocal task, the number of errors made with the right hand was greater compared to the control condition, but the number of errors made with the left hand was smaller compared to the control condition. Briggs interpreted these results through an attention switching model. However, it is also possible to explain the result with a functional cerebral distance model. The procedures used do not allow for distinction between the different explanations.

Hicks, Provenzano, and Rybastein (1975) used a functional cerebral distance model to explain the lateralized effects of concurrent verbal rehearsal and sequential finger movements. Verbal rehearsal interfered more with practiced finger sequences begun with the right hand than to sequences begun with the left hand. This difference is hypothesized to be a result of the functional cerebral distance between the areas controlling the different tasks.

Given the results of the Hollender studies and the support for the functional cerebral space model there exists a possibility that the response switching effect may be caused by the inability to quickly switch from one response modality to another. The purpose of Experiment 2 was to test this hypothesis.

If the response switching effect is indicative of the upper limit of how fast one can switch from one response modality to another, under conditions of a relaxed accuracy criterion, the observed results should be response rates and interresponse times that follow the pattern of results seen in Experiment 1. However, if the response switching effect is not due to an inability to quickly switch from one response modality to another but instead is due to some extraneous control of timing function, the response rates should indicate be higher than in Experiment 1. While the pattern of faster rates and shorter interresponse times may be attributed to a speed/accuracy tradeoff, the analyzed data will only include responses that are error free. Thus, the possibility of a fundamental inability to quickly switch from one response modality to another can be rejected as a cause of the response switching effect.

Method

Subjects. Six right handed Hampshire College students participated in this experiment. Each subject was paid an hourly wage plus bonuses.

Apparatus. The apparatus was identical to that used in Experiment 1.

Procedure. Except for the conditions and the feedback the procedure of Experiment 2 was identical to that of Experiment 1. The conditions differed in that subjects were instructed to perform a pure vocal condition (vocal/vocal), a pure manual condition (manual/manual), and a mixed condition. Instructions for the mixed conditions did not specify with which response (vocal or manual) the sequence should begin. Thus, subjects defined the condition (either vocal/manual or manual/vocal) of each trial in the mixed condition by the modality of the first response of the sequence.

The feedback differed from Experiment 1 in that at the beginning of each block the subject was instructed to complete the sequence as quickly and as accurately as possible. After each trial, the feedback consisted of a prompt that said, "Try to go faster." At the end of each block the feedback was identical to that of Experiment 1. It included the mean interresponse time and a score on which bonus money was based.

Results and Discussion

Response Rates. The mean response rates as a function of condition are presented in Table 4 (see page 23). Note the disparity in the number of self-initiated trials for the vocal-manual and the manual-vocal conditions. T-tests were conducted evaluating the differences in the pure vocal, the pure manual, and the mixed conditions. Response rates were averaged across renditions two through six. The first rendition was excluded from the analysis because the increased initiation time would decrease the rate. The response rate of the mixed condition was significantly faster than the pure vocal condition, $T(1,5) = 4.28$, $p < .008$; the response rate of the mixed condition was significantly faster than the pure manual condition, $T(1,5) = 3.95$, $p < .01$. No support for the response switching effect is provided. The result that the response rate of the mixed condition was faster than the response rates of the pure conditions indicates that the response switching effect is not due to an inability to quickly switch from one response modality to another.

Initiation Time. Table 5 (see page 19) presents the means for contrasting the responses of pure and mixed conditions. The initiation time for the vocal response in the pure condition was 60

Table 4

Mean production rate (responses/second) as a function of condition in Experiment 2.

Condition	Production Rate	Number of Trials in Condition
Vocal/Vocal	5.47	174
Manual/Manual	6.27	180
Vocal/Manual	8.34	42
Manual/Vocal	10.31	131

Table 5

Means for contrasting responses in pure and mixed conditions in Experiment 2.

Condition	Initiation Time	Interresponse Time	
		Response 1	Response 2
Pure Vocal	342	185	210
Mixed Vocal	282	190	134
Pure Manual	248	157	161
Mixed Manual	310	145	126

ms slower than the vocal initiation time in the mixed condition. However, the manual initiation response time in the pure condition was 62 *ms* faster than the manual initiation response time in the mixed condition.

Interresponse Time. Table 5 (see page 24) provides the interresponse times for contrasting responses. Examining the interresponse times that occurred in the first couplet position of the rendition, notice that in the mixed condition the vocal interresponse time is 5 *ms* slower than that of the pure condition. However, the manual interresponse time of the mixed condition is 12 *ms* faster than the manual interresponse time of the pure condition. Examining the interresponse times that occurred in the second couplet position, in the case of vocal and manual responses, interresponse times are faster in the mixed conditions. Thus, the effect of parallel production is accounted for by the faster interresponse times of responses in the second couplet position and by the faser manual interresponse times in the first couplet position.

Errors. The number of correctly alternated responses for each serial position is presented in Figure 2 (see page 26). In the manual-vocal condition only 31 of 131 trials were correctly alternated for six renditions. In the vocal-manual condition only 17 of the 42 trials were correctly alternated for six renditions.

Assuming the subjects were following the instructions "to alternate as quickly and as accurately as possible" and because the subjects were receiving bonus money for being fast and accurate, the question arises as to why is the error rate so high? A possible answer is that the subjects may have thought that they were

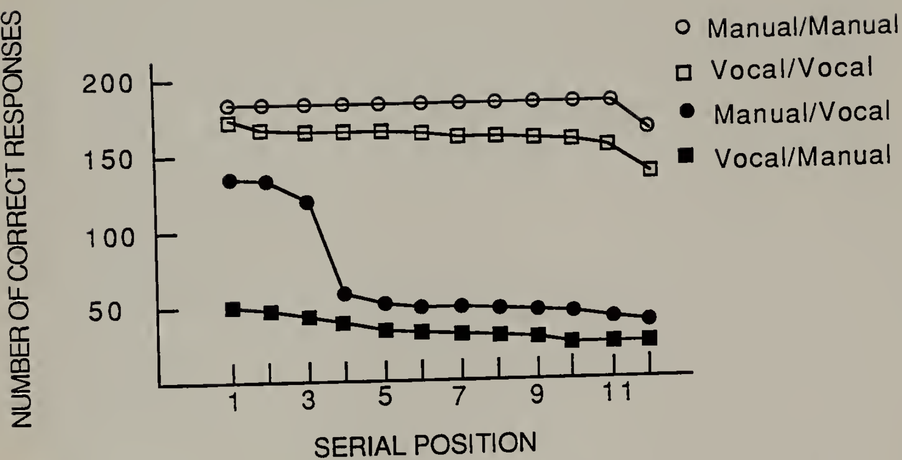

Figure 2. Number of correct responses as a function of condition and serial position.

alternating the responses correctly. Subjects may have been unaware of the timing difference between vocal and manual responses. The high error rates suggest that the motor system may not automatically control for production time differences and/or that the motor system may not automatically adjust for structurally different responses. The purpose of Experiment 3 was to examine the effect of production time difference of the responses and to examine the effect of the structural differences of the responses as possible causes of the response switching effect.

CHAPTER 4

EXPERIMENT 3

In review, the response switching effect refers to the phenomenon that the overall production rate associated with alternating between vocal and manual responses is slower than the rate of the vocal response repeated alone and the rate of the manual response repeated alone. The results of Experiment 1 verified the response switching effect through formal, systematic investigation. The results of Experiment 2 ruled out the possibility that the response switching effect was due to a fundamental inability to quickly switch from one response modality to another. Experiment 2 also raised the possibility that the motor system is unable to control for timing differences and/or structural differences of responses during an alternating task. The purpose of Experiment 3 was to examine the effects of production time differences and structural differences of responses as possible causes of the response switching effect. Experiment 3 also tested the generality of the response switching effect by extending the task to manual and pedal responses.

Method

Subjects. Ten right handed students from Hampshire College and the University of Massachusetts participated in this experiment. Each subject was paid an hourly wage plus bonuses.

Apparatus. The subject sat facing a video screen. Figure 3 (see page 29) illustrates the apparatus. With the forearms resting on the table, the subject placed his/her index, middle, and ring fingers in levers which were moved vertically between two stops when the

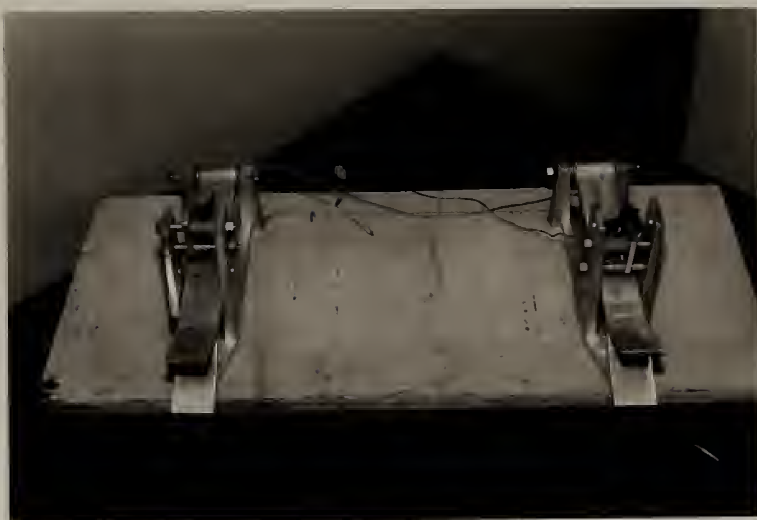

Figure 3. Photograph of apparatus used in Experiment 3.

subject flexed or extended the wrists. Subjects were instructed to refrain from flexing or extending at the finger joints. The amplitudes of the hand movements were adjustable by raising and lowering the top stops. With the heels lifted off the ground and resting on a wooden block to allow free flexion and extension of the ankles, the subject placed his/her feet in levers which moved vertically between two stops when the subject plantar flexed or dorsal flexed at the ankles. The amplitudes of each foot movement were adjustable by raising of lowering the top stops. The experiment was controlled through an Apple MacIntosh Plus computer equipped with a SCADIOS Interface (Logical Solutions, Amherst, MA).

Procedure. The task was to perform pedal and manual responses. The pedal responses consisted of moving a lever vertically between two stops. The amplitudes of the pedal responses were either 1.8 cm (pedal short) or 6.1 cm (pedal long). The manual responses consisted of moving a lever vertically between two stops. The amplitudes of the manual responses were adjusted so that the average time to complete the manual short response was equal to the average time to complete the pedal short response and so that the average time to complete the manual long response was equal to the average time to complete the pedal long response. The conditions of the experiment are presented on Table 6 (see page 31).

The procedure for adjusting the amplitudes of the manual responses was as follows. The subject performed 12 pedal responses (six renditions of a pedal/pedal condition) with either the left or right foot as quickly as possible, and the average response time (the

Table 6

*Conditions tested in Experiment 3.**

		Structure: Same		Structure: Different	
		Production Time: Same	Production Time: Different	Production Time: Same	Production Time: Different
First Response	Manual Short	M_SM_S	M_SM_L	M_SP_S	M_SP_L
	Manual Long	M_LM_L	M_LM_S	M_LP_L	M_LP_S
	Pedal Short	P_SP_S	P_SP_L	P_SM_S	P_SM_L
	Pedal Long	P_LP_L	P_LP_S	P_LM_L	P_LM_S

*M_S=Manual Short, M_L=Manual Long, P_S=Pedal Short, P_L=Pedal Long

time for the foot to move from the lower stop to the upper stop and return to the lower stop) was recorded. Half of the subjects used the left foot and half used the right foot. The side with which the subject performed this process is referred to as the critical side because the average time of these responses was used to adjust the manual responses. The critical side also refers to the side of the body that the subject's first response occurred. For example, in the manual short/manual short condition a subject in the left critical side group initiated a trial with a left manual short response. The critical side also refers to the side of the body with which the subject performed sequences of mixed conditions. For example, in the the manual short/pedal short condition, a subject in the left critical side group alternated these responses with the left hand and left foot, respectively. The subject repeated this process five times with the critical side foot. This portion of the adjustment procedure resulted in the time to be used for adjusting the production time of the appropriate (short or long) manual response. The subject then completed the process with the noncritical side foot. However, the recorded response times were not used for later adjustments.

After completing the pedal responses, the subject performed 12 manual responses (six renditions of the appropriate manual/manual condition) with the critical side hand as quickly as possible. The average response time and the amplitude of the manual response were recorded. The top stop was adjusted so that the response time difference between the average time of the critical pedal responses and the average time of the critical manual responses was minimized. This process was repeated five times and the amplitude which minimized the difference of the average manual and pedal response times most was used as that subject's respective short or long manual amplitude for the remainder of the experimental session. After finding the appropriate manual amplitude for the critical side, the amplitude of the manual apparatus on the noncritical side was set accordingly and the subject performed five sets of 12 manual responses (six renditions) with the noncritical side hand as quickly as possible.

The adjustment procedure was conducted for both short and long responses. The type (short or long) of pedal response with which the subject began the adjustment process was counterbalanced. The entire adjustment procedure lasted approximately 15 minutes.

After the adjustment procedure, the experimenter read instructions that explained each condition and the experimental procedure. At the beginning of each block, the subject was told which condition he/she should perform. As in the previous experiments, a block consisted of 10 trials, and a trial consisted of six renditions of the required responses. The subject performed one block of each condition. The order of presentation of conditions was random for each subject. The presentation of the warning and imperative signals was identical to the previous experiments. After each trial, the subject received feedback. The feedback was the same as that in Experiment 1. If the subject completed four or more correct renditions, the feedback included the mean response time, the number of correct renditions, and a prompt which said, "Try to go faster." Alternatively, if the subject completed less than four correct renditions, the feedback included the number of correct renditions and a prompt which said, "Try to be more accurate." This portion of the experimental session lasted approximately 60 minutes. The subject repeated both the adjustment procedure and the experimental procedure the following day.

Results and Discussion

Response Rate. An ANOVA evaluating the effects of first response (manual short, manual long, pedal short, pedal long) x structure (same as the first response, different from the first response) x time relation (same as the first response, different from the first response) was conducted on the mean response rate data averaged over renditions three though six from day two. The first two renditions were excluded from the analysis. The first rendition was excluded because the initiation response would have elevated the mean response rate. The second rendition was excluded from the analysis based on scatter plots which showed that the response sequence was in a state of instability or leveling off until the completion of the third rendition. For trials in which errors occurred, only those renditions occurring before the errors were included in the analysis.

Table 7 (see page 35) provides the mean response rates as a function of condition. The main effect of first response was significant, $F(3, 27) = 12.57$, $p < .001$. Subsequent analysis with a Newman-Keuls test indicated that the response rate of conditions beginning with a manual short response (6.59 res/sec) were significantly (Newman-Keuls = 3.84, $p < .05$) faster than conditions beginning with a manual long response (6.22 res/sec), a pedal short response (6.04 res/sec) and a pedal long response (5.10 res/sec).

Table 7

Mean production rate (responses/second) as a function of condition in Experiment 3.

Condition	Production Rate
M_SM_S	8.47
M_SM_L	6.66
M_SP_S	6.14
M_SP_L	5.10
M_LM_L	7.03
M_LM_S	7.43
M_LP_L	4.88
M_LP_S	5.23
P_SP_S	6.85
P_SP_L	5.62
P_SM_S	6.47
P_SM_L	5.24
P_LP_L	5.02
P_LP_S	5.44
P_LM_L	4.66
P_LM_S	5.27

The main effect of structure was significant, $F(1, 9) = 11.69$, $p < .007$; the mean rate of conditions in which the structure of the two responses was the same was 6.56 res/sec, and the mean rate of conditions in which the structures of the two responses were different was 5.41 res/sec. The main effect of time relation was significant, $F(1, 9) = 16.75$, $p < .002$; the mean rate of conditions in which the time relation was the same was 6.19 res/sec, and the mean rate of conditions in which the time relation was different was 5.78 res/sec. Thus, the response switching effect is seen when alternating between responses from different structures and when alternating responses with different time relations.

Two interactions were significant, the first response x structure interaction, $F(3, 27) = 18.27$, $p < .001$, and the first response x time relation interaction, $F(3, 27) = 17.39$. $p < .001$. Figure 4 (see page 37) illustrates the first response x structure interaction. Notice that the rates of conditions beginning with manual responses were slower when paired with responses from different structures (Newman-Keuls = 4.91, $p < .05$) than when paired with responses of the same structure. However, the rates of conditions beginning with pedal responses did not change as a function of the structure of the second response. Figure 5 (see page 38) illustrates the first response x time relation interaction. Newman-Keuls analysis indicated that the rates of conditions beginning with manual short and pedal short responses were slower (Newman-Keuls = 3.90, $p < .05$) when the time relation was different than when the time relation was the same. However, the Newman-Keuls ($p > .05$) analysis indicated that the rates of conditions beginning with manual long and pedal long responses did

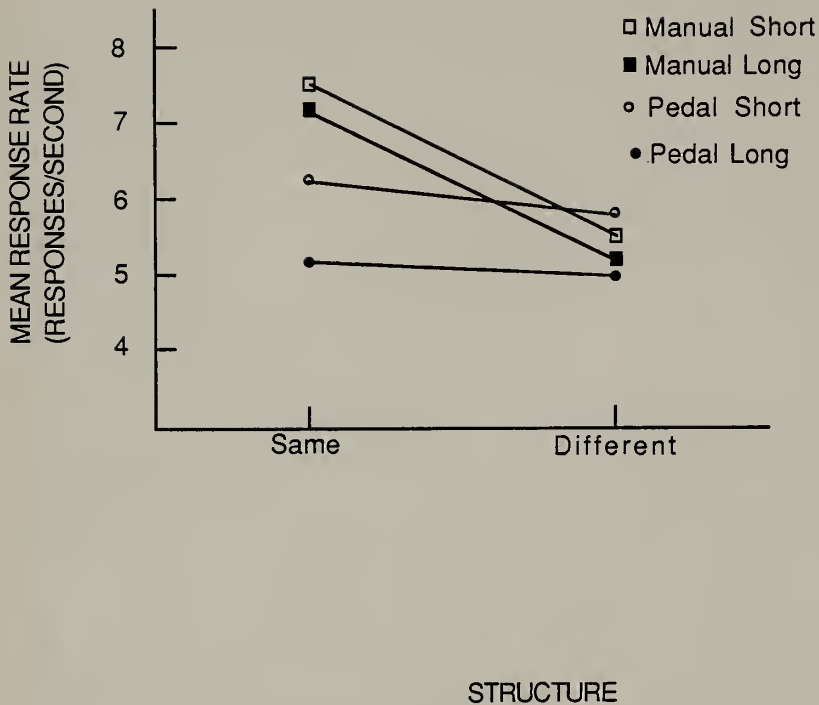

Figure 4. Mean response rate as a function of first response and structure in Experiment 3.

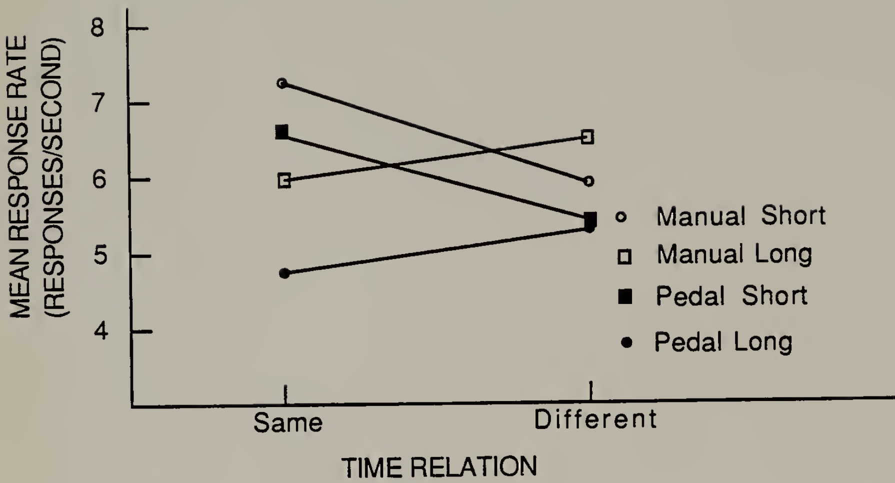

Figure 5. Mean response rate as a function of first response and time relation in Experiment 3.

not change as a function of the time relation. Note that while rates of conditions beginning with short responses slowed when paired with a long response the rates of conditions beginning with a long response did not speed up when paired with a short response.

Initiation Time. An ANOVA evaluating the effects of critical side (left, right) x first response (manual short, manual long, pedal short, pedal long) x structure (same as the first response, different from the first response) x production time (same as the first response, different from the first response) was conducted on the mean initiation time (T1) of session two. No main effects were significant. The first response x production time interaction was significant, $F(3, 24) = 4.793$, $p < .01$. Figure 6 (see page 40) illustrates this interaction. Initiating a response sequence in which the timing of the component responses is the same, takes the same amount of time regardless of whether the response sequence begins with a manual or a pedal response. However, when the production time of the first and second responses is different, sequences beginning with manual short responses take significantly (Newman-Keuls = 4.17, $p<.05$) longer than sequences beginning with pedal short or pedal long responses.

Velocity. Velocity was examined as a concomitant measure of response timing. Table 8 (see page 41) presents the mean velocities for the first and second responses of each condition. These velocities were taken from the means across subjects of responses over renditions two through six. The distances traveled and the response times were from switch opening to switch opening. Because of the crude measure, long distances and long response times, there was a

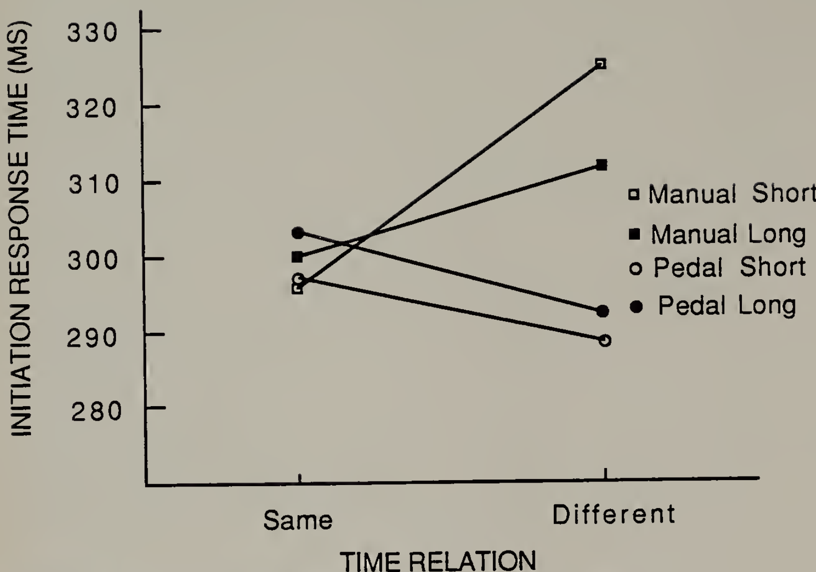

Figure 6. Initiation response time as a function of first response and time relation in Experiment 3.

Table 8

Mean Velocities (centimeters/second) of noninitial responses as a function of conditon in Experiment 3.

Condition	Couplet Position1	Couplet Position2
M_SM_S	22	22
M_SP_S	16	10
M_SM_L	17	33
M_SP_L	13	30
M_LM_L	35	36
M_LP_L	24	28
M_LM_S	36	20
M_LP_S	27	9
P_SP_S	12	12
P_SM_S	11	19
P_SP_L	10	33
P_SM_L	9	27
P_LP_L	30	30
P_LM_L	26	24
P_LP_S	31	10
P_LM_S	30	14

possibility that the measure would not be sensitive enough to pick up any effects. However, this was not the case. If subjects executed the responses with different production times (e.g., M_SM_L, M_SP_L, M_LM_S, M_LP_S, P_SP_L, P_SM_L, P_LP_S, P_LM_S) at the same velocity, the responses would not be alternated correctly because of the amplitude difference. A possible solution would be to hold the effector associated with the

shorter amplitude in a "waiting position". This would result in equal velocities for the two responses. However, examining Table 8 (see page 33), the velocities are not equal. This suggests that if timing adjustments are needed, the control mechanism does not merely insert delays between the movements to achieve equal velocities. Instead, the result suggests that timing is controlled in part through velocity modulation or a physical concomitant of velocity.

In sum, the results of Experiment 3 support the hypothesis that structural differences and production time differences are in part causes of the response switching effect. Experiment 3 extends the response switching effect from the vocal and manual modalities to the manual and pedal modlaities. The fact that the effects of structure and time relation do not interact for any of the dependent measures suggests that structure and time relation affect different aspects of the execution of alternating responses from different response modlaities (Sternberg, 1969).

CHAPTER 5

GENERAL DISCUSSION

A well established fact in movement control is that the motor system is capable of utilizing parallel production to increase the production rate of alternating manual responses and to increase the production rate of alternating vocal responses (Gentner, 1982; Gentner, Grudin, and Conway, 1980; Kent & Moll, 1972). The response switching effect refers to the phenomenon that the response rate associated with alternating between responses from different response modalities is slower than the response rates of each response executed alone. Experiment 1 verified the specific phenomenon that when one alternates between saying the syllable "ba" and tapping the right index finger, the overall response rate is slower than when "ba" is repeated alone and when the right index finger is repeatedly tapped.

Experiment 2 and Experiment 3 examined possible causes of the effect. Experiment 2 ruled out the possibility that the effect is caused by a fundamental inability to quickly switch between response modalities. Instead, when subjects performed with a lax accuracy criterion, the response rates indicated that subjects could alternate more quickly between response of different modalities than between responses of the same modality. Experiment 3 was conducted in order to determine the effect of structural differences and the effect of production time differences as possible causes of the response switching effect. Experiment 3 also examined the generality of the response switching effect. The response switching effect was extended to a task that involved the alternation of manual and pedal responses. The results suggested that structural differences and production time differences are in part causes of the response switching effect. Further, because the effects of structure and the effects of time relation did not interact in any of the dependent measures, structural differences and production time differences appear to affect different aspects of the execution of alternating manual and pedal responses.

Central Clock Model

After considering several models to account for the response switching effect, the most appropriate model seems to be the central clock model. The model assumes that a central clock controls the initiation of responses. The rate of responding is controlled by inserting delays before responses when necessary. The length of the delay is based on the production time differences of the responses being produced. Figure 7 (see page 45) illustrates the central clock model.

In the pure condition the clock initiates each response as soon as the previous response is completed. In the alternating condition in which the first response is associated with the faster production time (e.g., manual/vocal), the central clock initiates both responses at the same time, and because of the production time difference, the two responses are executed in the correct order. On the other hand, in the alternating condition in which the first response is associated with the slower production time (e.g., vocal/manual), delays are inserted before the initiation of the faster responses. The length of the delay is set according to the production time difference of the responses. Thus, in the pure condition the central clock prepares

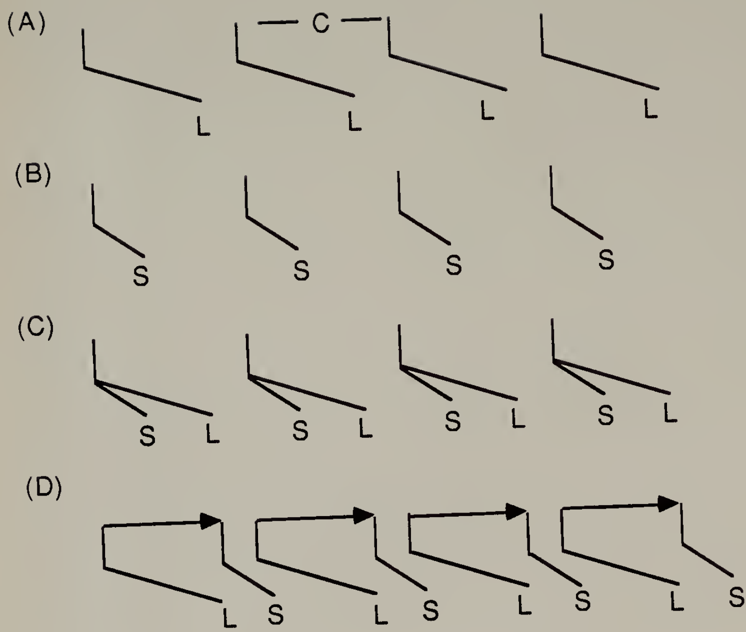

Figure 7. Schematic representation of the central clock model. C represents the rate of the central clock. S represents the response associated with the shorter production time. L represents the response associated the longer production time. The arrow represents the planned delay. See text for explanation.

and initiates a single response before each response in the sequence. In the alternating condition in which the first response is associated with the faster production time, the central clock prepares and initiates two responses before each rendition in the sequence. In the alternating condition in which the first response is associated with the slower production time, the central clock prepares and initiates two responses and a delay before each rendition in the sequence.

The assumptions of the central clock model are that preparation time increases as the complexity of the motor program increases and that preparation time increases when the insertion of a delay is necessary. Therefore, preparation time is a function of the number of responses to be prepared and a function of the planned delay between the responses. Preparation time occurs before the initiation of the first response in all sequences, before each response in the pure conditions, and before each couplet in alternating conditions. The model makes several predictions that are confirmed in the three experiments.

Predictions Concerning Response Rate. In terms of response rate, the model predicts that the rate of the pure condition should be greater than the rate of the mixed condition. This prediction follows from the fact that in the pure condition the central clock prepares and initiates a single response before each response in the sequence. In the alternating conditions, the central clock prepares and initiates two responses and a delay before each rendition in the sequence. Thus, the model predicts that the response switching effect should occur during alternating conditions. The results of Experiment 1 and Experiment 3 support this prediction. The results of Experiment 2 suggest that when accuracy is not a priority in the task, the response rate of the mixed condition is faster than the response of the pure condition.

Recall that in the condition in which the first response is associated with the faster production time, the two responses are initiated simultaneously. The difference in the production time of the responses influences the length of the delay to be inserted before the faster response. In order to achieve the fastest rate of responding while maintaining accuracy, a logical strategy would be to immediately initiate a response couplet as soon as the previous slower response is completed. With the use of this strategy, the model predicts that the difference in the response rates of the pure condition and the mixed condition in which the first response is associated with the faster production time should be less than the difference in the response rates of the pure condition and the mixed condition in which the first response is associated with the slower production time. For Experiment 1 the prediction is that the difference in the response rates of the vocal/vocal and the manual/vocal conditions should be less than the difference in the response rates of the vocal/vocal and the vocal/manual conditions. As seen in Table 1 (see page 8) this prediction was supported. The same prediction is made for Experiment 2. However, because of the disparity in the number of trials for the manual/vocal and the vocal/manual conditions, this comparison is questionable. The results from Experiment 3 (see Table 7, page 28; Figure 4, page 29; and Figure 5, page30) suggest that the the structural relation and the time relation of the responses in the sequence influence the response rate.

The model predicts that the response rate of the condition in which the first response is associated with the faster production time should greater than the response rate of the condition in which the first response is associated with the slower production time. This prediction follows from the fact that in the condition in which the first response is associated with the slower production time that in addition to preparing and initiating two responses before each response couplet, a delay must also be prepared and initiated before each response couplet in the sequence. The results of Experiment 1 support this prediction. The response rate of manual/vocal condition was 6.40 res/sec and the response rate of the vocal/manual condition was 4.73 res/sec. Again, Experiment 3 provides converging evidence that the important factors in the response rate is the structural relation and the time relation of the responses.

<u>Predictions Concerning Initiation Time.</u> The model makes several predictions concerning initiation time. The model predicts that the initiation time of responses beginning the pure condition should be less than the initiation time of that response beginning a mixed condition. The is because in the pure condition the initiation time consists preparing and initiating a single response. In the alternating condition in which the first response is associated with the faster production time, the initiation time consists of preparing two responses. In the alternating condition in which the first response is associated with the slower production time, the initiation time consists of preparing two responses and a delay based on the

computation of the production time difference of the two responses. For Experiment 1 the prediction is that the initiation time of response beginning the pure conditions should be less than the initiation times of those responses beginning the respective mixed conditions. As seen in Table 2 (see page 9), this prediction was supported. The same prediction is made for Experiment 2. Again, the disparity of the number of trials for the vocal/manual and the manual/ vocal conditions makes this comparison questionable. Looking at the conditions in which the first response was a manual response, the initiation times are in the direction of the prediction; mixed condition initiation times are less than pure condition initiation times (see Table 5, page 23). The initiation times of the conditions beginning with a vocal response are in the opposite direction of the prediction. Namely, initiating the pure condition was faster than initiating the mixed condition. The results from Experiment 3 suggest that the important factor is the difference in the time relation not the difference in structure. The first response x time relation interaction illustrated in Figure 14 (see page 37) suggests that initiating a response sequence in which the time relation of the responses is the same, takes the same amount of time regardless of whether the response sequence begins with a manual or a pedal response. However, when the time relation of the responses is different, sequences beginning with manual short responses take longer than sequences beginning with pedal short or pedal long responses.

In Experiment 1 the difference in initiating the pure manual condition and the pure vocal condition is 58 *ms*. The difference in initiating the mixed conditions is 99 *ms*; initiating the vocal/manual condition takes longer. This result suggests that preparing a sequence in which one response per time step is to be initiated is more complicated than preparing a sequence in which two responses per time step are going to be initiated.

Predictions Concerning Interresponse Time. The model makes several predictions concerning interresponse times. In considering these predictions note that in the mixed conditions, the interresponse times arise from different factors. If the central clock rate is C, and the slow response and the fast response efferent times are S(e) and F(e) respectively, the interresponse times of the responses in the mixed conditions can be derived. In the condition in which the first response is associated with the faster response (F/S), the interresponse time of the fast response is

$$F(F/S) = C + F(e) - S(e) \quad (1)$$

and the interresponse time of the slow response is

$$S(F/S) = S(e) - F(e). \quad (2)$$

In the condition in which the first response is associated with the slower response (S/F), the interresponse time of the fast response is

$$F(S/F) = C + F(e) - S(e) \quad (3)$$

and the interresponse time of the slow response is

$$S(S/F) = C + S(e) - F(e). \quad (4)$$

The interresponse times of the fast responses depend on the same factors for each condition. However, the interresponse times of the slow responses are different for the two conditions. In one condition, S(F/S), the slow interresponse time is dependent on S(e) and F(e). In the other condition, S(S/F), the slow interresponse time is also dependent on the central clock rate.

There are two ways to estimate the difference in the production time of the vocal and manual responses in Experiment 1. One way is to use the difference in the interresponse times of the two responses in their pure conditions, 30 *ms*. The other is to use the difference in the interresponse times of the two responses in the manual/vocal condition, 36 *ms*. The model predicts that the vocal interresponse time of the pure condition should be more similar to the vocal interresponse time of the manual/vocal condition (difference of 40 *ms*) than the vocal/manual condition (difference of 100 *ms*). The results of Experiment 1 support this prediction.

The model predicts that the slower interresponse time should be faster in the condition in which the first response is associated with the faster production time than in the condition in which the first response is associated with the slower production time. In Experiment 1 the prediction is that the vocal interresponse time should be faster in the manual/vocal condition than in the vocal/manual condition. As seen in Table 2, this prediction was supported. Again, the disparity in the number of trials in Experiment 2 make this comparison questionable.

Predictions Concerning Error. In terms of errors, in the condition in which the first response is associated with the slower production time, there is a delay that must be prepared and initiated that is not needed in the other conditions. Thus, there is a greater chance for errors to occur. As seen in Experiment 1, this prediction was supported. There were a greater number of errors in the vocal/manual condition than in the manual/vocal condition. In Experiment 2, the disparity in the number of errors in the vocal/manual and the manual/vocal conditions suggest that given the opportunity to prepare either of the sequences, the system is more likely to prepare for the condition in which both responses are initiated at a single time step. This suggests that this condition is the easier condition. The error data of Experiment 1 provides converging evidence for this assumption.

In sum, the central clock model assumes that a central clock controls the initiation of responses. The rate of responding is controlled by inserting delays before responses when necessary. The length of the delay is based on the production time differences of the responses being produced. The model makes predictions concerning response rate, initiation time, interresponse time and errors which are supported by the results of the three experiments.

Levels of Explanation

A phenomenon that may be related to the response switching effect is reported by Kelso and his colleagues (Haken, Kelso, & Bunz, 1985; Kay, Kelso, Saltzman, & Schoner, 1987; Kelso, Schoner, Scholz, and Haken, 1987). The phenomenon consists of abrupt transitions in human hand and finger movements as a result of changes in cycling frequency. The method Kelso and his colleagues use in exploring this phenomenon is referred to as "phenomenological synergetics." It consists of empirically determining the nature and dynamics of order parameters, particularly during nonequilibrium phase transitions, followed by the identification of relevant subsystems and their dynamics. This approach is founded in the principles of physical biology and the use of concepts of dynamics (Kelso, 1981).

Kelso (1981) argues that spatial and temporal order are consequences of the dynamics of the biological system. The need for control through motor programs and timing mechanisms does not exist. Instead, spatial and temporal order are merely physical properties of systems in a state of energy flux. A discussion of the modeling of this phenomenon provides an alternative approach to the modeling of the response switching effect that has been presented.

The specific phenomenon is as follows. When subjects were instructed to move the index fingers or wrists in a rhythmic and cyclic manner, two stable states of performance were observed. Subjects performed in either an in-phase mode where homologous muscle groups contracted simultaneously or in an anti-phase mode where homologous muscle groups contracted in an alternating fashion. When subjects began the task in the anti-phase mode, as cyclic frequency was increased beyond a critical value, subjects changed to an in-phase mode of performance. Further experimentation revealed that only two stable phase-locking states exist (Kelso, Schoner, and Haken, 1987), that critical fluctuations of the order parameter (relative frequency) exist (Kelso, Scholz, and Schoner, 1986), that critical slowing before the transition exists (Kelso, Scholz, and Schoner, 1986), and that kinematic relationships between frequency, amplitude, and velocity exist (Kay, Kelso, Saltzman, and Schoner 1987).

These findings provide a sample of the nature and dynamics of the order parameter (relative frequency). The next step is to identify the subsystems and dynamics thereof. Haken, Kelso, and Bunz (1985) presented a model in which the hand and finger movements were described by nonlinear limit cycle oscillators with nonlinear coupling between the two oscillators. The control parameter is cyclic frequency. The model gives rise to oscillatory performances as an attractor in the (x, x) phase plane. Kelso, Schoner, , and Haken (1987) expanded the model to include an external pacing force, transition characteristics, and the switching time (time to move from anti- to in-phase states). Thus, the model gives rise to many of the characteristics seen in the empirical data.

The similarity in the response switching effect and the phenomenon explored by Kelso and his colleagues (Haken, Kelso, and Bunz, 1985; Kay, Kelso, Saltzman, and Schoner, 1987; Kelso, Schoner, Scholz, and Haken, 1987) is seen in the fact that an important characteristic is the production time or the cyclic frequency. While Kelso (1981) argues against and ignores the possible role of a timing mechanism, it is possible that what he and his colleagues are actually modeling are the characteristics of a timing mechanism. How does one distinguish between a mechanism and the dynamics of the mechanism in behavior? One argument for the need for a timing mechanism concerns the role of practice. If timing is a consequence of a biological system, is it that a practiced musician has turned a once unstable state of this biological system into a stable state of this biological system? The empirical and theoretical result that only two phase-locked modes exists suggests that practice should not allow for the creation of stability from instability.

In terms of a model that includes a timing mechanism, the Kelso phenomenon simply might be explained in the same way as the response switching effect. When parallel production is possible, independent systems execute the responses at the desire rates. However, if the difference in the production times of the responses reaches a critical point, a timing mechanism must adjust either one or both of the production rate so as to decrease this difference. Thus, in the vocabulary of dynamics, the control parameter becomes production time difference. In modeling the Kelso phenomenon, the control parameter is cyclic frequency. A subject's critical frequency is related to that subject's preferred cyclic frequency. An alternative explanation is that the preferred cyclic frequency is merely the frequency that minimizes the difference in the production times of the required responses. Further, the critical frequency might be the point at which the timing mechanism can no longer make adjustments to an individual system. Instead, after reaching the critical frequency, timing must be controlled through adjustments in both systems executing the required responses. This might explain the abrupt switch from two modes to a single in-phase mode of performance. Under the timing model explanation, a prediction is that the greater the difference in the production time of the required responses the lower the critical cyclic frequency should be. The Kelso phenomenon is reported for the fingers and the wrists. From published results (Kay, Kelso, Saltzman, and Schoner, 1987; Kelso, Schoner, Scholz, and Haken, 1987) it seems that the critical frequency occurs between two and three Hz. The production time differences are similar for both sets of effectors. Thus, a good test for the prediction is not provided.

Baldissera, Cavallari, and Civaschi (1982) reported a similar experiment in which cyclic movements of the hand and foot coupled according to a "direction principle." In the experiment the hand and foot coupled so that the effectors moved simultaneously in the same direction (e.g., hand flexion with plantar flexion when the forearm is prone). When the subjects were instructed to move the effectors in the opposite direction (e.g., hand extension with plantar flexion when the forearm is prone), subjects displayed poor performance. Further, as the cyclic frequency was increased, subjects instructed to maintain movements in the opposite direction displayed a transition to movements in the same direction. The same results were shown when the forearm was supine. In the supine position the coupling was inverted compared to the prone position. Thus, muscles that were easily coupled in the prone position were difficult in the supine position. The authors reported that the transition from movements in the opposite direction to movements in the same direction were not always abrupt. This is in contrast to the results reported by Kelso and his colleagues (Haken, Kelso, and Bunz, 1985; Kay, Kelso, Saltzman, and Schoner, 1987; Kelso, Schoner, Scholz, and Haken, 1987). Baldissera, Cavallari, and Civaschi also reported that the transition usually occurred at about three Hz. However, it is difficult to compare this critical frequency to those of Kelso and his colleagues because in the Baldissera, Cavallari, and Civaschi experiment frequency was not controlled and subjects performed hand and foot movements rather than two hand movements.

Baldissera, Cavallari, and Civaschi (1982) explained their data in terms of anatomical organization. Preferential coupling occurs through the coordination of spinal activity that coactivates a set of fibers which later branch to the different effectors. Nonpreferential coupling is said to occur because of convergence of opposite commands to the fibers (e.g., excitatory to one effector and inhibitory to the other effector).

While the response switching effect and the coupling phenomena of Kelso, Schoner, Scholz, and Haken (1987) and of Baldissera, Cavallari, and Civaschi (1982) are similar, the explanations are different. The response switching effect was explained with a psychological model. Kelso et. al. explained their phenomenon through "phenomenological synergetics," and Baldissera et. al. explained their phenomenon with an anatomical explanation. Each provides a different level of explanation. Because the levels are so different, it is possible that each explanation is describing the same mechanism or some aspect of it. Believe, however, that the critical factor in each level of explanation involves timing. In the response switching effect a critical factor is production time; in the Kelso et. al. model the control parameter is cyclic frequency; and in the Baldissera et. al. explanation parallel excitation/inhibition is crucial in for nonpreferential coupling. Kelso et. al. (1987) provided theoretical models that explained their phenomenon on two levels; that of the individual hands and the coupling behavior of the two hands. A direction of future research is aimed at exploring if each of these levels of explanation is in fact describing the same mechanism.

In conclusion, Experiment 1 verified the specific phenomenon that when one alternates between saying the syllable "ba" and tapping the right index finger, the overall response rate is slower than when the "ba" is repeatedly said and when the right index finger is repeatedly tapped; this was referred to as the response switching effect. Experiment 2 ruled out the possibility that the response switching effect was merely a fundamental inability to switch quickly between response modalities. Experiment 3 suggested that the effect of structural differences and the effect of production time differences are possible causes of the response switching effect and extended the response switching effect to different effectors, manual and pedal. Further, the results of Experiment 3 suggested that structural differences and production time differences affect different aspects of the execution of alternating manual and pedal responses. The central clock model was discussed as a means of understanding the execution of alternating responses from different response modalities. Finally, related phenomena and the explanations of these phenomena in the literature were compared to the response switching effect.

Future research will be directed at temporal control. Development of the central clock model will allow for a better understanding of the execution of alternating responses from different modalities and for understanding conditions which allow for parallel production as opposed to the response switching effect. Finally, development of the central clock model will provide a basis for comparing explanations of phenomena related to the response switching effect.

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