DOCUMENT RESUME

ED 042 213 CG 005 752

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TITLE Proprioceptive Factors in Operative Timing.
INSTITUTION Illinois Univ., Urbana. Children's Research Center.
SPONS AGENCY Illinois State Dept. of Mental Health, Springfield.; National Inst. of Mental Health (DHEW), Bethesda, Md.
PUB DATE 68
NOTE 25p.

EDRS PRICE EDRS Price MF-$0.25 HC-$1.35
DESCRIPTORS Adolescents, Cognitive Processes, Educational Research, *Feedback, *Junior High School Students, *Learning Processes, Males, *Motor Reactions, Problem Solving, Spelling, *Time Factors (Learning), Time Perspective

ABSTRACT

Time estimation is improved when the interval is filled with a motor response, with the proprioceptive feedback (PFB) presumably acting as a mediator. Altering the resistive dynamics of a handle moved 60 centimeters to fill a two-second interval manipulated the PFB from the response. Spelling aloud 2-, 3-, and 4-letter words during the motor response controlled the PFB from spelling and prevented overt counting. Eighty-four 11-14 year old boys were given immediate KR, the lapsed time for the motor response, for 50 or 60 trials according to the design. Only the condition reducing PFB to a minimum, no movement and no spelling, prevented accurate estimates, but above a minimal level accuracy, consistency and rapidity of learning increased with increasing PFB. (Author)

Proprioceptive Factors in Operative Timing[1]

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Adaptive motor responses require accurate direction, force, and timing to be successful. Human mechanisms for controlling the force and direction have been described (Matthews, 1933), but how the human measures duration is not certain. The mechanisms governing the measurement of short durations has caused speculation among psychologists. The hypotheses proposed during the preceding century have been reviewed recently by Michon (1967). One of them suggested that intervals are measured in terms of the stimuli generated by a response made during the interval and was called the sensory motor feedback hypothesis.

Münsterberg in 1889 suggested that time measurement was made in terms of afferent stimuli generated by activity filling the interval. He claimed that when durations of longer than one-third of a second are to be measured, the subject relied exclusively on feelings of tension and relaxation in the muscles. This supposition was supported by Sears (1901); Gilliland, Hofeld and Eckstrand (1946); and Goldfarb and Goldstone (1963) who used spatial patterns to facilitate the estimation of intervals. Similarly Ss asked to estimate an interval frequently and successfully adopt the strategy of counting, "One-thousand-one, one-thousand-two,..." The increased accuracy seems easily explained in this case since the subject produces and reproduces finite events that are counted until the required duration has passed.

The finite events most consistently available to a subject are voluntary motor responses. Since these are constrained by the physical properties of the effectors involved and objects in the environment that they act upon, the constancy of these events is limited by the ability of the subject to control the duration of the response by reproducing the magnitude, direction, and extent of the necessary forces. Clausen (1950) defined as "operative estimation" the estimation of a temporal interval that was bounded by the start and finish of an operation that filled the interval, and this definition is used here. During operative estimation the interval is filled with the stimulus events generated within the operator himself which are paired with knowledge of the result. These stimuli encode information for the position of the limb and the tension of its musculature and arise from proprioceptors situated in the tissues of the effector (Wenger, Jones & Jones, 1956).

Several researchers have produced evidence that the presence of proprioceptive feedback from limb action during an interval to be timed has increased the accuracy or reduced the variability of the estimate (Adams & Creamer, 1962; Goldfarb & Goldstone, 1963; Goldstone, Boardman & Lhamon, 1958; Grose, 1964; Weber, 1927). This study follows from the findings of Ellis, Schmidt and Wade (1968) which showed that a large, as opposed to small, movement caused an operative timing task to be learned more quickly and to produce less error. One problem was to determine whether different types and levels of instrumental resistance that were known to influence tracking (Bahrick, Bennett & Fitts, 1955; Bahrick, Fitts & Schneider, 1955; Howland & Noble, 1953), also influenced operative time estimation.

An alternative direction to the mediation of intervals has been provided by the examination of the effects of verbalization during the interval on time estimation. Gilliland (1940), and Gilliland and Humphreys (1943) both allowed some subjects who were trying to estimate an interval to count. They found little difference in accuracy whether the subject counted or not, implying that covert cues are as good as overt cues in estimating time without knowledge of results. However, when knowledge of results was provided, the counting group very rapidly correlated their internal cues with external data and performed more accurately. The non-counting group still had only mental events to pair with the external error data, and were as variable as before. These findings supported the suggestion that the subject converted a task requiring subjective estimation of time into one that required a comparison with overt self-generated events. Goldstone, Boardman, and Lhamon (1958) determined if the presence of kinesthetic cues were necessary for the counting during the interval to be effective and found that overt was better than covert counting. This left unanswered the question whether the children used auditory cues associated with overt counting or the proprioceptive cues generated by uttering the counts.

To evaluate the effects of variations in control dynamics a large, simple, and discrete motor response was used to fill an interval. Since one condition in the experiment generated minimal feedback and the other conditions varied the mode and magnitude of the proprioceptive feedback during a movement time of two seconds, it was postulated that the more feedback generated during the interval, the more accurately it would be estimated. The responses with less feedback would, therefore, be more difficult and might force the subjects into using a strategy of counting overtly. This would have confounded the effects so overt counting was controlled by imposing a secondary overt verbal task on all subjects that varied the nature and amount of verbal feedback independently of the conditions. During the motor response, the subjects were required to spell a random arrangement of two-, three-, and four-letter words at a conversational volume while auditory feedback was eliminated by very high intensity simulated white noise. Thus, this secondary task provided the opportunity to test whether proprioceptive feedback from speech influenced the timing of a motor response.

Method

The Task

The operative estimation problem was to learn to move a handle along a straight trackway 60 centimeters in precisely two seconds. Knowledge of results was given immediately after each of 50 trials. The rectilinear response was controlled by a nearly frictionless slide (cursor) that the subject moved along a track mounted on a table. The subject could not see the track or any of the auxiliary apparatus because of a wooden screen and one-way mirror erected before the subject. Movement away from the right end started a timing circuit which was stopped by the arrival of the cursor near the left end, thus measuring the duration of the movement. The cursor drove a hub by means of a light cable. Resistances proportional to position, velocity, or acceleration could be added to the cable or hub and detailed specifications for the apparatus can be found in Ellis (1968).

The minimal control condition (Mincon) allowed minimal movement (2.5 millimeters) and minimal resistance and thus minimal movement or resistance feedback. A movement control condition (Movcon) involved 60 centimeters of virtually unresisted movement requiring 7.49 million ergs to complete the response. Movcon provided cues for position and minimal cues for tension. The three experimental conditions required driving a light aluminum wheel so that the wheel alone, the minimal inertia condition (Minert), provided a control for the experimental conditions and required the expenditure of 14.18 million ergs of work to produce a correct response. The three experimental conditions involved considerable muscular effort and the work done during the responses was equal under each experimental condition. The maximal position resistance (Maxpos) involved an elastic band which provided a resistance proportional to the position of the cursor on the track. The maximal velocity resistance (Maxvel) used a viscous-like resistance generated by a powerful electromagnetic brake, and the other condition involved mass added to the periphery of the aluminum wheel and provided resistance proportional to acceleration (Maxacc). To produce a correct response the maximal position, velocity, and acceleration resistances required the expenditure of 52.80, 52.85, 52.90 million ergs, respectively.

During the motor response the Ss were required to spell a simple two-, three-, or four-letter word to prevent the use of covert verbal cues. The words were selected from those having a frequency of more than 1,000 times per million in books for children eight through twelve years of age (Thorndike and Lorge, 1944). The words were rear-projected onto a three-inch square screen before the subject by means of a film-strip projector.

The 50 words appeared in random order on the film-strip and the film was wound alternately forwards and backwards as the Ss were tested. Since the film-strip broke on two occasions and testing was continued using the longer tail of the film-strip, the number of words of the three lengths was not exactly counterbalanced for a small number of subjects.

Subjects

The Ss, 84 right-handed boys in Grades Seven and Eight, were assigned randomly to six groups of fourteen subjects each. The boys had a mean age of 13.15 years, a mean height of 62.7 inches, and a mean weight of 112.9 pounds. Their mean I.Q. of 114.5 corresponded to the mean I.Q. of the school.

Procedure

Six groups, or one for each treatment, practiced for 40 trials with knowledge of results and a fifteen-second rest after each trial. They then had a one-minute rest and took ten more similar trials under the same condition. Lapsed time for each response was read from a digital counter display, rounded to .01 second and recorded. This measure, ignoring the decimal point, was the score given the subject. Absolute error was derived as lapsed time minus two seconds with the sign ignored. A measure of response consistency was determined by computing intravariance over successive blocks of five measurements and rapidity of learning was determined by the number of trials to a criterion of three out of four trials in 1.90 through 2.10 seconds.

A question arose after data collection started as to the possible effect of not spelling. Consequently, eleven subjects in each of the six groups were given ten additional trials when overt verbalization was denied them. The subjects were watched carefully by the experimenter and if any overt timing behavior, apart from the response, was detected the subjects were told to stop. Thus, two different analysis of the influence of speech on the motor response were possible. The effect of the length of the word spelled was determined for the groups of fourteen subjects that experienced 50 trials, and the effect of removing the spelling task was determinable for the groups of eleven subjects that performed 50 trials with spelling and were then transferred to performing without overt verbalization for a further ten trials.

Results

Motor task

The mean lapsed time exhibited by the subjects for each of the 50 trials (Table 1) showed considerable differences on the early trials but then followed a similar decelerating curve from an initial under-estimate toward the target time. The asymptote under-estimated the target for Mincon, but the remaining groups appeared to be on target. The general shape of the curves indicated that all groups learned to estimate two seconds with considerable accuracy.

Insert Table 1 about here

Analysis of lapsed time variance showed that the differences between conditions when summed over trials was significant (F = 3.61 [5,78]

$p < .01$) and trial means summed over conditions were also significantly different ($F = 10.72$ [49,3822] $p < .01$). *Post hoc* comparisons demonstrated that group performances ceased to be significantly improved by Trial 15. On the first three trials the treatments appeared to produce different effects after which all groups showed similar performance changes. This apparent interaction was also significant ($F = 1.57$ [245,3822] $p < .10$). Movcon seriously under-estimated; Mincon, Maxpos, and Maxvel were surprisingly accurate; and Minert and Maxacc over-estimated on the first trial. On the next two trials all group means, irrespective of condition, were adjusted towards an under-estimate in the range 1.5 to 1.7 seconds. Thereafter, the curves asymptoted similarly.

Since the treatment means summed over trials contained a systematic under-estimate during the first 14 trials the data were re-analyzed to determine whether the treatments produced different estimates once learning was over. When the means were summed over Trials 21-50, they showed that Ss in Mincon produced a large under-estimate (1.92 seconds) while the mean performance in the other conditions were accurate (Movcon, 1.98; Minert, 2.02; Maxpos, 1.98; Marvel, 2.02; and Maxacc, 2.03 seconds, respectively). Analysis of lapsed time variance showed that the treatments produced a significant effect on the terminal performance ($F = 2.87$ [5,78] $p < .05$), whereas, the previous analysis of the interaction showed that after Trial 3 the differences between treatments were insignificant.

Post hoc comparisons showed that Minert, Maxvel, and Maxacc produced significantly different and more accurate estimates than Mincon, which consistently under-estimated.

The first three trials suggested that the Ss, even though they were receiving accurate knowledge of results, attempted to approximate some prior estimate of two seconds. This was an estimate of approximately 1.5 to 1.7 seconds. The resisted movement conditions were slower than the unresisted Movcon suggesting that the Ss had expectations as to the "feel" of the control and programmed a response accordingly. Movcon, being virtually frictionless, was moved too quickly while Minert and Maxacc, both of which presented their greatest resistance at the initiation of the response, were too slow. The subjects required two trials to adjust their responses to remove the effects of the differing dynamics of the control, and then required thirteen more trials to correct their estimates of two seconds. After learning was completed, the treatment involving movement over 60 centimeters with and without resistances produced accurate estimates, while the treatments requiring minimal movement and tension produced serious under-estimates.

Absolute error (Table 1) showed very similar results to lapsed time from which it was derived and, in the interests of brevity, is not reported in full. However, in the analysis of terminal performance (Trials 31-50) Maxvel (.164 seconds) and Maxacc (.151 seconds) exhibited significantly smaller mean absolute errors than Mincon (.232 seconds).

The variance of Ss about their own means (intravariance) (Table 1), which represented response consistency, was computed for ten successive blocks of five trials. The intravariances were somewhat dissimilar on the first block but, thereafter, appeared to vary similarly over trials with Mincon and Movcon producing the largest, Minert and Maxpos intermediate, and Maxvel and Maxacc the smallest intravariances. The difference among treatments were significant ($\underline{F}$ = 4.53 [4,78] p < .01) and the treatment means showed a trend of increasing within-subject consistency with increasing proprioceptive feedback. Newman-Keuls post hoc comparisons (Winer, 1966, p.80, p.309) showed that Minert, Maxvel, and Maxacc were significantly more consistent than Mincon. Thus, the additional movement and tension varying with position during the interval, did not significantly reduce inconsistency, while the addition of both levels of inertia and tension varying with velocity did.

A significant "block" effect ($\underline{F}$ = 24.36 [9.45] p < .01) was created by extreme intravariance in the first block. This rapid reduction was probably artifactual, caused by the augmentation of the intravariance by the steep trends in the data due to learning in the early trials. The markedly reduced intravariance in Block 2 persisted with only slight diminution over the remaining blocks so post hoc comparison of the effects among treatments seemed unnecessary. The absence of a significant interaction ($\underline{F}$ = 0.84) indicated that the trends for treatments tended to remain parallel over successive blocks.

The number of trials taken by a S to learn to equal a criterion performance (Table 1) established a priori was used as a dependent variable to differentiate the effect of treatments on rate of learning. The criterion established for this study was defined as the number of trials required for a subject to produce any three from four successive trials within the range 1.90 to 2.10 seconds inclusive, thus requiring both accuracy and consistency of performance. The trend in these scores is reflected in the treatment means. Mincon required the most trials to learn to criterion and the addition of movement, and minimal inertia increased the rapidity of learning. Of the three experimental conditions, Maxpos was little better than Minert, its control condition, whereas Maxvel and Maxacc required markedly fewer trials. The trend towards more rapid learning with more proprioceptive feedback was shown to be significant by analysis of variance (F=3.84 /‾5.78_7 p<.01). Post hoc comparisons showed that Marvel and Maxacc required significantly fewer trials to learn the criterion than Mincon. Thus tension cues for velocity and acceleration produced significantly more rapid learning to a criterion requiring accuracy and consistency than a condition in which the proprioceptive cues were minimized.

Verbal task

The group mean lapsed times for the three lengths of words spelled are shown in Figure 1. There was an overall trend for all groups to produce longer and more accurate estimates with increasing word length. When summed over treatments two- and three-letter words tended to be under-estimated (1.88 and 1.9 seconds, respectively) while four-letter words produced a very accurate mean lapsed time (2.01 seconds). The condition generating minimal proprioceptive feedback by the operation of a toggle switch (Mincon) produced an unusually large under-estimate when spelling two-letter words (1.72 seconds) suggesting an interaction between treatment and number of letters.

Insert Figure 1 about here.

The increasing mean accuracy with increasing number of letters produced a significant effect (F = 76.77 /‾ 2,4163 7 p<.01) indicating that within the range of letters tested and summing over treatments, the more letters spelled the more accurate the response. The treatments by letters interaction was significant ($F = 2.45$ [10,4163] $p < .01$). *Post hoc* analysis confirmed that the lapsed time for Mincon while spelling two-letter words was significantly smaller than the other conditions, and that there were no significant differences between the treatments when spelling three- and four-letter words. This indicated that a two-letter word provided insufficient feedback to enable Ss denied gross motor behavior during the interval to produce estimates as accurate as those for longer words and appreciable motor behavior. Three- or four-letter words enabled Ss denied gross motor action during the interval to perform like Ss with gross motor actions.

Insert Figure 2 about here.

The absolute errors associated with the different treatments for the different word lengths are shown in Figure 2. The number of letters exerted an effect as shown by an analysis of absolute error variance ($F = 6.71$ [2,4182] $p < .01$). The mean absolute error was lowest for the movements accompanied by the spelling of three-letter words (.215 seconds), whereas, those of the two- and four-letter words were larger (.234 and .244 seconds, respectively). This indicated that unlike the lapsed time effects where increasing feedback from letters produced more accurate estimates, the spelling of three-letter words enabled the subjects to perform with least error if not the greatest accuracy. This supported subjective reports from adults trying the task that performing the motor task while spelling three-letter words felt easiest because the rhythm of spelling seemed to fit the response. However, although it perhaps felt better and presumably reduced the Ss intravariance around the mean response for three-letter words, it biased the motor response to produce the under-estimate reported in the lapsed times.

The interaction between treatments and letters was significant ($F = 1.93$ [10,4182] $p < .05$) and showed the same pattern as that for lapsed time from which it was derived. The group experiencing least feedback, those subjects operating the toggle switch, whilst spelling the shortest words, produced the largest error, arguing again that below a minimal level of feedback the subject could not accurately estimate the time.

After 50 trials, eleven Ss from each group were transferred to a condition where overt verbalization was denied them for a further ten trials. The cessation of spelling caused a marked drop in the mean lapsed times for the group with minimal proprioceptive feedback (Mincon; 1.93 to 1.75 seconds) but the other groups performances remained essentially unchanged (Figure 3). This suggested an interaction between the presence and absence of spelling and treatments. Analysis of lapsed time variance produced a significant treatments effect ($F = 7.83$ [5,60] $p < .01$) and an effect of spelling and not spelling ($F = 4.98$ [1,60] $p < .05$) and an insignificant interaction ($F = 2.21$ [5,60] $p > .05$). Inspection of the figure shows that these effects can be ascribed to the gross under-estimate by Mincon after the cessation of spelling.

Insert Figure 3 about here

The mean absolute error showed a tendency common to all groups for absolute error to increase with cessation of spelling (Figure 4). As with lapsed time, the significant effect for treatments ($F = 8.98$ [5,60] $p < .01$) and between spelling and not spelling ($F = 10.83$ [1,60] $p < .01$) both resulted from the marked inaccuracy of Mincon after cessation of spelling. This marked effect for Mincon, combined with some slight differential effect for the other treatments, also resulted in the significant interaction ($F = 4.35$ [5.60] $p < .01$). Post hoc analysis showed no significant difference between treatments with spelling and only Mincon differed significantly from the other treatments after cessation of spelling. Proprioceptive feedback from appreciable movement or from spelling without appreciable arm movement seemed sufficient for relatively accurate operative time estimation. But time estimation, even with knowledge of results, was considerably worse when both types of proprioceptive feedback were removed.

Insert Figure 4 about here

Discussion

The addition of tension varying with velocity and acceleration enabled the Ss to learn to reproduce the operation filling the interval with less absolute error, greater consistency, and fewer trials than Ss provided with either movement cues only or the minimal cues associated with operating a toggle switch. These results ran counter to those of Howland and Noble (1953) who showed that simple harmonic tracking was improved by position ues but not by velocity or acceleration cues. The contradiction suggested that the tasks were different since the resistive devices in the present study were modeled on those established by Howland and Noble.

The task used by Howland and Noble required the subject to track a target continously and the presence of momentum in the system increased complexity since it had to be counteracted by a response from the antagonistic muscles. In a discrete ballistic response, the subject can let the limb and control run without generating any further action to interfere with that produced by the initial impulse, thus providing simpler information that allows accurate adjustments between trials. A similar argument can be advanced for the velocity cues. The effects of the feedback depended on the dynamics of the task, with information for velocity and acceleration favoring discrete operations, while position information would seem to favor continuous tracking.

Proprioceptive feedback and control dynamics influenced operative timing under the various conditions. The hypothesis that greater proprioceptive feedback produced better estimates was supported by Maxvel and Maxacc producing better performances on a variety of measures than the control conditions. However, although the same work was done, Maxpos did not produce significantly better performance, presumably because it was more complex than Maxvel or Maxacc, since it required the recruitment of progressively more force as the cursor was moved against the elastic resistance. Thus by altering the control dynamics, two factors appeared to interact, producing different effects according to the nature of the task. Increasing tension cues for velocity and acceleration improved operative time estimation, since the response was simple, but providing tension cues for position produced a more complex task that did not produce a similar improvement.

The effects of spelling on performance showed that spelling three- and four-letter words allowed Ss denied other feedback during the interval (Mincon) to perform almost as accurately as the groups moving the cursor. This clearly supported the findings of Goldstone, Boardman and Lhamon (1958) who showed that counting aloud produced more accurate estimates of an interval. The present results also resolved the issue as to whether the critical feedback from counting aloud was proprioceptive or auditory, since the high intensity, simulated white noise received during the response masked air-conducted or bone-conducted sound. Thus, the crucial feedback was proprioceptive.

The spelling of two-letter words provided inadequate feedback and the responses accompanied by only two letters were similar to the under-estimates made by Ss during the first few trials. Thus, once a minimal level of motor involvement was allowed to fill an interval, the S could utilize the feedback generated and learn to estimate the interval via a motor response with considerable accuracy.

Accurate time estimation depended on proprioceptive feedback, which supported the sensory motor hypothesis. Minimal feedback was necessary to maintain reasonably accurate responses and only the removal of all definable content from the interval disrupted performance. Proprioceptive feedback from moving 60 centimeters with or without added resistance or spelling three- or four-letter words produced accurate estimates. Spelling two-letter words without movement provided insufficient feedback to overcome the initial tendency to under-estimate the time and the withdrawal of spelling disrupted performance.

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FOOTNOTES

[1]This study comprised part of a Ph.D. dissertation submitted under the sponsorship of Dr. A. W. Hubbard to the University of Illinois, 1968 and was given preliminary presentation as two short papers to the Second International Congress on Sport Psychology, Washington, D.C., 1st November, 1968. It was supported in part by funds provided by the State of Illinois Department of Mental Health and by USPHS Research Grant No. MN-07346 from the National Institute of Mental Health.

TABLE 1

Effects of Treatments and Practice on Performance

		Mincon	Movcon	Minert	Maxpos	Maxvel	Maxacc	All
				Lapsed Time (seconds)				
	1	1.94	1.17	2.18	2.01	2.03	2.39	1.95
	2	1.38	1.44	1.81	1.85	1.88	1.89	1.71
	3	1.44	1.51	1.65	1.62	1.70	1.74	1.61
	4	1.52	1.77	1.68	1.63	1.74	1.89	1.70
Trials[a]	5	1.86	1.80	1.84	1.68	1.90	1.82	1.82
	6 - 10	1.75	1.83	1.83	1.82	1.90	1.89	1.83
	11 - 15	1.76	1.95	1.95	1.83	1.98	1.95	1.90
	16 - 20	1.88	1.96	1.97	1.93	2.08	2.08	1.98
	21 - 50	1.92	1.98	2.02	1.98	2.02	2.03	1.99
				Intravariance (second)				
	1	.250	.170	.195	.231	.114	.133	.182
Block[b]	2	.060	.096	.050	.035	.035	.045	.053
	3 - 10	.086	.066	.045	.046	.042	.039	.054
				Trials to Criterion				
Group Mean		29.93	24.28	20.28	19.86	14.78	13.21	20.39

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[a]Data condensed above since analysis showed that performance reached an asymptote by Trial 15 and that Treatments interacted with Trials for only two trials.

[b]Intravariance was reduced only during the first block of 5 trials so blocks 3 - 10 were condensed.

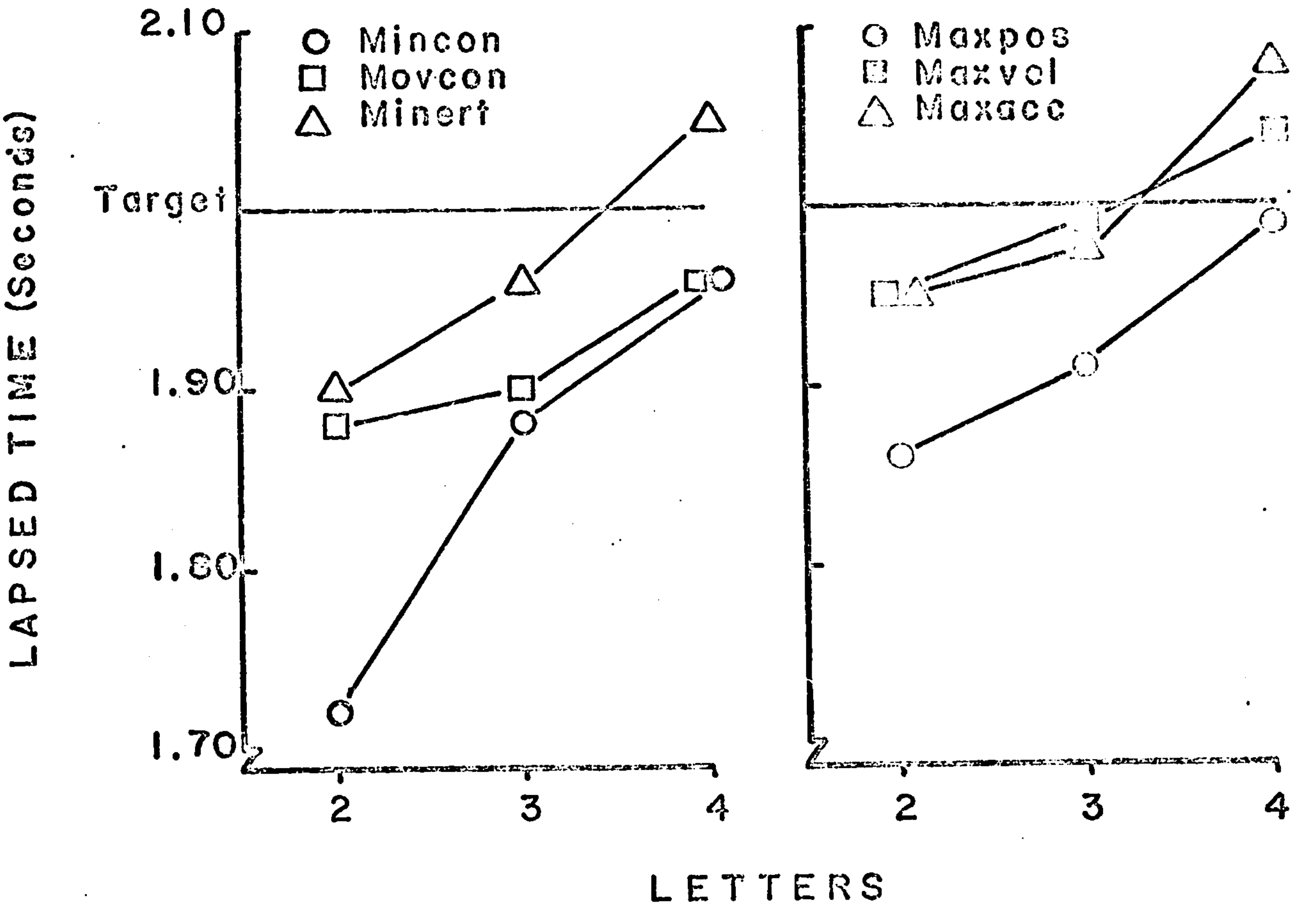
Figure Captions

Figure 1. Lapsed times while spelling 2,3, and 4 letter words.

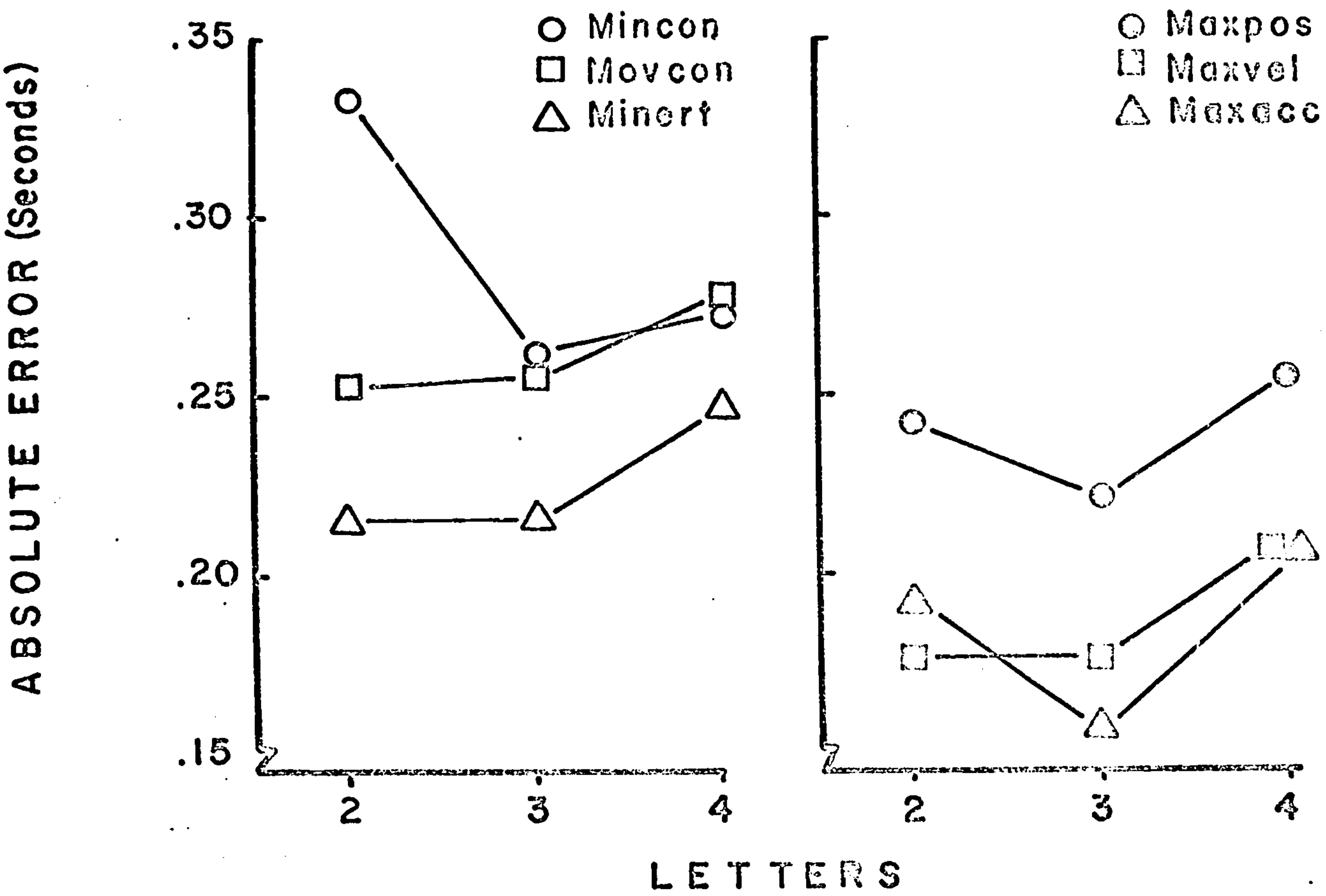
Figure 2. Absolute errors while spelling 2,3, and 4 letter words.

Figure 3. Effects of withdrawing spelling on lapsed times.

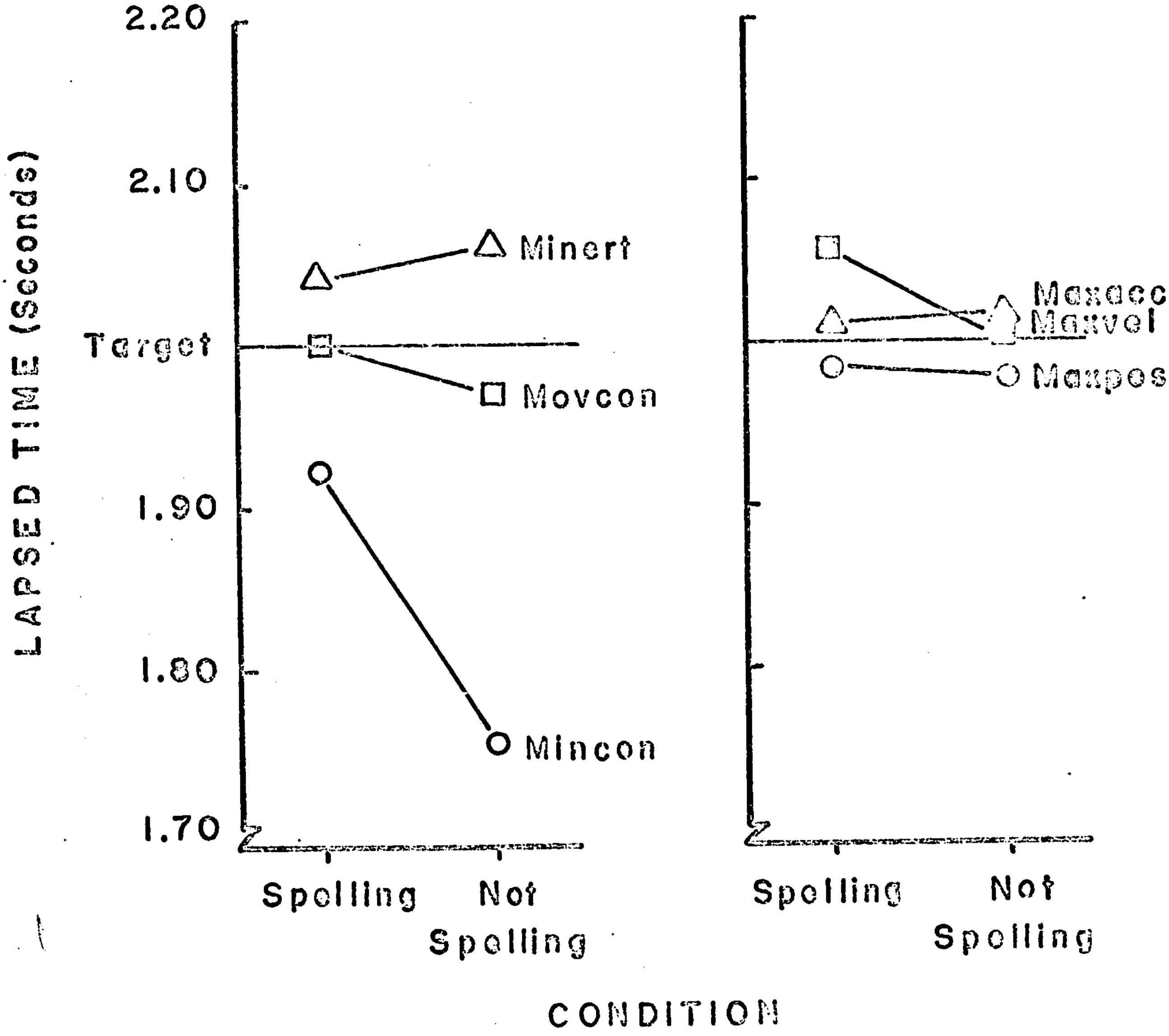
Figure 4. Effects of withdrawing spelling on absolute errors.



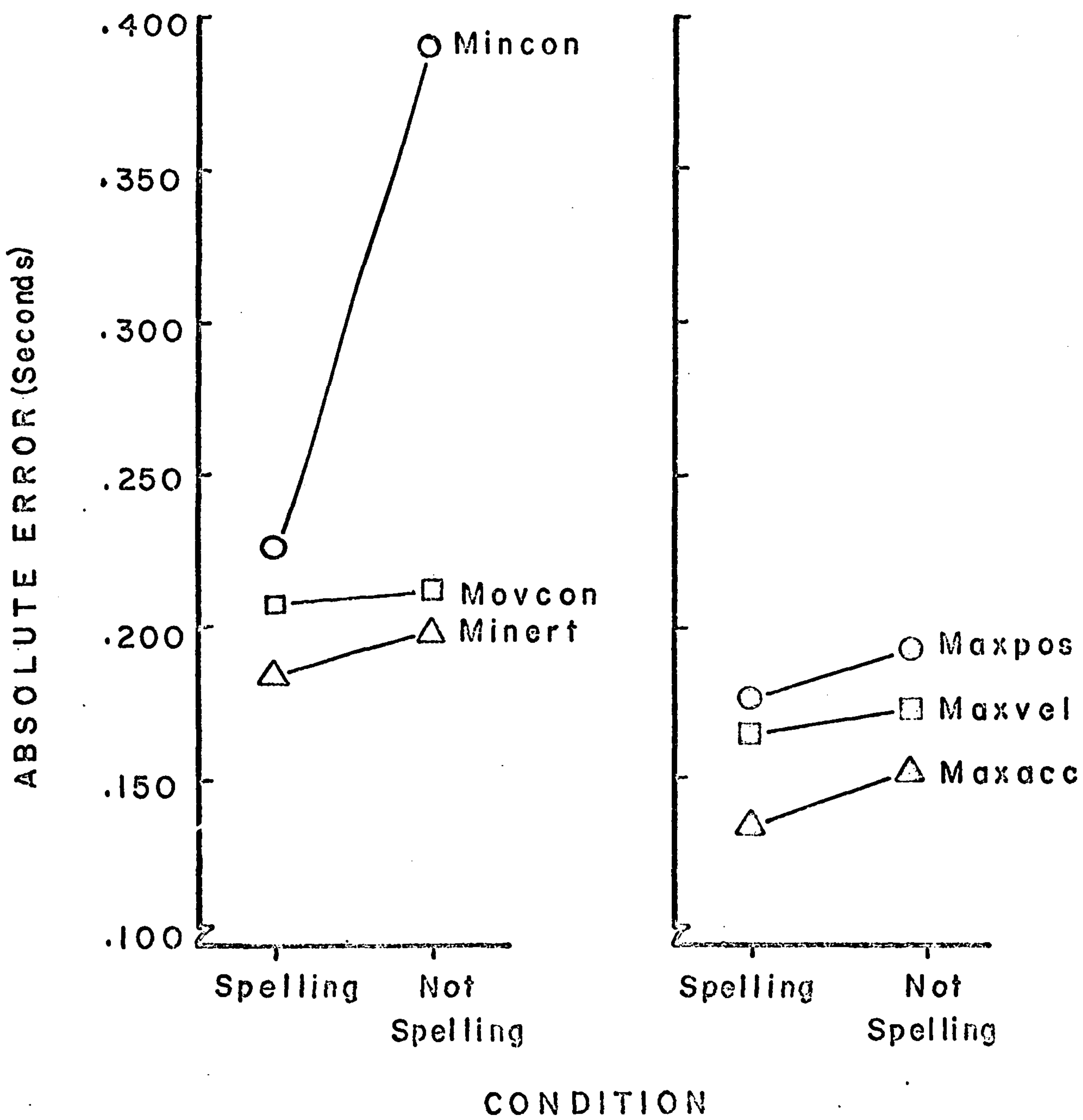
2.10
1.90
1.80
1.70
Target
LAPSED TIME (Seconds)
Mincon
Movcon
Minert
Maxpos
Maxvel
Maxacc
2
3
4
LETTERS



ABSOLUTE ERROR (Seconds)
.35
.30
.25
.20
.15
Mincon
Movcon
Minert
Maxpos
Maxvel
Maxacc
2
3
4
2
3
4
LETTERS



LAPSED TIME (Seconds)
2.20
2.10
Target
1.90
1.80
1.70
Minert
Movcon
Mincon
Maxacc
Maxvel
Maxpos
Spelling
Not Spelling
Spelling
Not Spelling
CONDITION



ABSOLUTE ERROR (Seconds)
.400
.350
.300
.250
.200
.150
.100
Mincon
Movcon
Minert
Maxpos
Maxvel
Maxacc
Spelling
Not Spelling
Spelling
Not Spelling
CONDITION