Some Experimental Evidence For and Against a Parametric Conception of Movement Programming

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In Experiment 1, subjects were supplied with prior information about 1, 2 or all dimensions (the active hand, direction, and extent) of a pointing movement. RTs showed that dimensional effects were found in highly compatible stimulus-response conditions, dimensional specifications times were underadditive, and the difference in RT between dimension values when that dimension remained to be specified, disappeared when the dimension was precued. In Experiment 2, subjects were required to name target color after a set of colored targets was presented as a pre-cue, and dimensional effects disappeared. In Experiment 3, a target was presented as a prime, followed by presentation of either the same or a different target. As compared to Experiment 1, dimensional effects were amplified. In conclusion, when two or more movement dimensions have to be specified simultaneously, dimension values are independently selected, then integrated in a compound programming operation.

The fact that actions must be spatially and temporally ordered to reach their goal has indicated that movements are precisely planned before execution. Consequently, the concept of the motor "program" remains one of the most influential in the field of motor control studies. This research was supported by a research grant (No. 82 60 16) from Institut National de la Santé et de la Recherche Médicale.

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be made about the duration and timing of the programming operations.

In the precuing technique (cf. Rosenbaum, 1980), the experimental setup requires a subject to make movements after a preparatory signal (the precue) has supplied the subject with partial information about one or several movement dimensions, for instance, the direction or extent of aiming movements executed from a common home position toward different spatially located targets. Insofar as the central programming system is able to use such partial information to specify the corresponding movement dimensions, the programming time component of RT will be shortened, in comparison with conditions in which no information about movement dimension is given in advance. This shortening can be interpreted as the specification times of the precued dimensions. This may differ according to the movement dimensions considered. Furthermore, one can infer that the set of specification operations is serially processed if specification times are additive with number of precued dimensions. When the RT shortening associated with the precuing of one movement dimension only occurs when another dimension is also simultaneously precued, one can infer that the serial specification process is ordered, the latter dimension necessarily being specified before the former.

In the priming technique (cf. Rosenbaum & Kornblum, 1982), the preparatory signal, or prime, supplies the subject with complete target information about movement dimensions. However, within a series of trials, the prime is followed either with a high probability by an expected target (a valid prime) or with a low probability by an unexpected target (an invalid prime). Pointing movements toward the expected and unexpected targets can, therefore, differ in one, several, or all dimensions, according to the spatial locations of both targets. The RT lengthening for pointing movements to an unexpected target is interpreted as the sum of the times necessary to despecify and to respecify movement dimensions for which the prime was invalid. The inferences about the timing of specification operations that can be drawn from a comparison of RTs observed in conditions that differ in the number and nature of unprimed dimensions are identical to those provided by the precuing technique.

This methodological background for studying the parametric programming of movements can be summarized as follows. As it has been used, the priming technique is based on the measurement of the time necessary to partially modify a complete but wrong programming process, whereas the precuing technique is based on the time necessary to complete a partial but correct programming process. The associated changes in RT are interpreted as specification or programming times in precuing and as compound despecification and respecification (or deprogramming and reprogramming) times in priming. This difference suggests that changes in RT observed when advance information about movement dimensions is manipulated in the precuing technique ought to be amplified when the same information is manipulated in the priming technique. The present set of studies was designed to compare results produced by both techniques with the same experimental setup.

The priming technique has been utilized for studying the dimensional programming of spatially oriented movements in only one experiment (Larish & Frekany, 1985) as far as we know. Two series of studies by Rosenbaum (1980) and by Goodman and Kelso (1980) with the precuing technique produced partly contradictory results. These studies originated the debate about the generality and even the validity of a programming process based on assembling separable operations specifying movement spatial dimensions.

In Rosenbaum's (1980) studies, subjects performed, without visual control, pointing movements toward targets whose spatial location could be described by combining three binary spatial dimensions: (a) side, involving a choice between either the left or right arm, (b) direction, either farther from or nearer to the subject, thus involving either extension or flexion, and (c), distance, either long or short. The imperative signal was a colored dot on a display panel, with a one-to-one mapping of colors to targets. A precue supplied the subject with information about either 0, 1, 2, or 3 movement dimensions. It was formed by a set of either 1, 2, or 3 letters; each of them indicated the value that each precued dimension had. Each precue was changed to a cross symbol when the corresponding dimension was not precued. From a detailed analysis of the set of RTs observed, Rosenbaum concluded that motor programming is a parametric process in that each movement dimension is independently specified, specification times differ as a function of the dimensions considered, and specification operations occur serially but without a strict order.

These conclusions were challenged by Goodman and Kelso (1980), who replicated Rosenbaum's (1980) results with an experimental setup similar to that of Rosenbaum. They failed to find any experimental support for a dimensional specification process when a spatially compatible arrangement of stimuli and responses was used (viz., when the spatial arrangement of precues, imperative signals, and targets was the same). Consequently, Goodman and Kelso suggested that changes in RT associated with a precuing of movement dimensions resulted from the somewhat artificial experimental setup adopted by Rosenbaum. The arbitrary incompatible stimulus-response (S–R) code that associated colors with targets and letters to movement dimensions (and that made a long training period of learning necessary) suggested that the dimensional effects resulted mainly from coding operations. For instance, by translating information provided by the precue into a language (for instance, that of the Euclidean geometry) similar to that used by the experimenter to describe the spatial configuration of targets, the subject is thus artificially factoring movements into dimensions, a factoring process that is not usually done by the nervous system when planning actions in more natural conditions, as Goodman and Kelso claimed. However, Bonnet, Requin, and Stelmach (1982) and Larish and Frekany (1985), with a spatially compatible S–R code, collected data leading to conclusions quite similar to Rosenbaum's. The crucial problems of the generality and the reality of the parametric specification model of movement programming thus remain unresolved. The first aim of our study was to address these problems.

The second aim of this study was to specify the nature of the processes that are triggered by advance information about movement dimensions. The two possible interpretations of the results from precuing and priming studies that the frame-
work of information-processing models allows have been extensively discussed elsewhere (Requin, 1985). One interpretation involves a preprocessing conception, in which RT shortening is viewed as resulting from a backward displacement of processing operations before the imperative signal. The other interpretation involves a presetting conception, in which RT shortening is viewed as resulting from a change in the functional efficiency of the programming operations that intervene after the imperative signal occurs. For instance, RT shortening when movement direction is precued results either from the fact that the corresponding programming operation now takes place during the foreperiod or from the fact that the programming of movement direction that is triggered by the imperative signal is facilitated. We must emphasize that these alternative interpretations make different predictions about changes in RT associated with different dimension values when the corresponding movement dimension either is specified in advance or is not. If the RTs (and by inference the specification times) of the two values of a movement dimension differ when the dimension is not specified in advance, the preprocessing conception implies that such a difference disappears when the movement dimension is precued, because movement values are programmed before the imperative signal occurs. This argument is very similar to that made by Kerr (1979), Klapp (1977), and Klapp, Wyatt, and Lingo (1974) on the basis of experiments in which the duration of a keypress response was cued in advance or not: RT differences present between long and short uncued responses disappeared when the responses were cued. The presetting conception implies that such RT differences are either maintained or reduced, depending on whether the effect of precuing the movement dimension either equally or proportionately accelerates the programming of dimension values after the imperative signal. To address this question, differences in RT between dimension values of each dimension when the dimension is either precued or uncued were systematically examined in our study. Preliminary results have been presented elsewhere (Lépine & Requin, 1983).

Experiment 1

The aim of this first experiment was to determine whether the programming of spatially oriented movements, executed in conditions of high S-R spatial compatibility, proceed through a dimensional specification process. Therefore, this experiment was a replication of Rosenbaum’s (1980) study but with an experimental setup similar to that adopted in Bonnet, Requin, and Stelmach’s (1982) study. In this setup, precues, imperative signals, and targets were spatially superimposed. This setup ensured a high level of S-R spatial compatibility. However, some substantial changes were made to the experimental designs used in these previous studies. First, the set of precuing conditions was extended in order to provide more data suitable for testing a serial specification model of movement programming; one must recall that this test is based on accepting the null hypothesis that specification times are additive. Second, the experimental setup used in the precuing technique implies that a change in the number of precued movement dimensions is most often achieved by a change in the size of the set of cues that forms the precuing signal. In such a case, the number of precued movement dimensions and the number of alternatives in the RT task are, therefore, confounded variables in the RT changes (Zeplanik, Shapiro, & Carter, 1982). However, although that cannot be avoided when all movement dimensions are precued (a precuing condition equivalent to a simple RT task), it can be avoided when fewer dimensions are cued. That is, a precuing signal can be selected that precues either one or some movement dimensions or that provides no dimensional information to the subject. This latter procedure has already been exploited by Goodman and Kelso (1980; the so-called “ambiguous” precuing conditions of their Experiments 3 and 4) in a blocked-condition design and by Larish and Frekany (1985) in their “S-R constant condition.” Here, we systematically introduce this condition, as a control in a mixed-condition design. Third, in contrast to most other studies (but see Bonnet, Requin, & Stelmach, 1982), simple (monoarticular) hand pointing movements were used. The spatial dimensions of these movements can be easily described in terms of their biomechanical parameters.

Method

Subjects. Twenty right-handed subjects, 13 women and 7 men, between the ages of 20 and 40 years, participated in the experiment. They were paid 30 francs ($5) per hr. They were not informed about the purpose of the experiment.

Apparatus. The subjects sat at a table on which two handles, one for each hand, were horizontally arrayed (see Figure 1). In order to make the subject’s posture comfortable when she or he grasped both handles and moved them vertically, (a) the proximodistal axes of either forearm were not exactly in sagittal planes but slightly converged forward, and likewise they were not exactly in a horizontal plane but were oriented slightly upward; (b) the midlateral axis of the first finger joint was not exactly in a frontal plane but was oriented slightly forward and was not exactly in a horizontal plane but was oriented slightly downward. Moreover, the wrist and elbow rested on stands, and their position was thus fixed. On each handle, two springs opposing upward and downward handle rotations were arranged so as to compensate for the hand weight when the handle was in a central rest position (when the forearm and hand were in the same plane). When moving either handle, the subject independently controlled the position of two pointers on a vertical display panel located at eye level about 60 cm in front of the subject. This was accomplished by means of a mechanical transmission formed by a cable attached to the handle. Because the handles were moved by rotating the hand around the wrist axis, their angular displacements did not exceed 15°, so distortions from a linear transducing function were quite weak.

Two vertical slots, 10 cm long and 2.5 cm wide, 1.5 cm apart in the midsagittal plane, were cut out of a black screen that hid the mechanical transmission device and made only the pointers and the display panel visible (see Figure 1). Pointers were formed by horizontal black bars, 4 mm wide, on which was drawn a horizontal white index, 1 mm in width. They moved in front of the display panel on which 8 targets were arranged according to the combination of 3 binary spatial dimensions. In terms of target location, these dimensions were the left or right side in reference to the midsagittal plane, the vertical location (above vs. below) and the distance (proximal vs. distal) in reference to the midsagittal plane; in terms of parameters of the monoarticular hand movement to reach targets, the corresponding dimensions were the active hand (left vs. right), the direction (extension vs. flexion), and the extent (long vs. short). Left and right
targets were separated by 5 cm. Proximal and distal targets were located at 20 mm and 40 mm from the center of each slot, respectively. Targets were formed by white translucent plastic rectangles, 5 mm high, behind which a yellow light-emitting diode (LED) could be illuminated. In order to render pointing accuracy requirements identical (e.g., according to Fitts', 1954, law), the vertical length of proximal and distal targets was 8 mm and 16 mm, respectively. A red LED was located just adjacent to each target. For each slot the central rest position of the pointer was indicated by a green LED. At the center of the display panel, a gaze fixation point was formed by a 4 mm white square on the black screen.

Procedure. The subject's task was to displace one of the pointers from the central rest position as quickly as possible to one of the targets when illuminated. Before this task, the illumination of either one red LED or a set of red LEDs was used as a precue to provide the subject with information about the target location. The detailed timing of a trial was as follows: The preceding pointing movement triggered an intertrial interval (ITI) of 4 s, during which the subject was required to adjust both pointers to the starting position; a correct adjustment was made when both green LEDs, which were permanently illuminated during the experiment, were masked by the pointers. The ITI ended with the presentation of the precue, the illumination of one or several red LEDs for 1 s. When these were turned off, a preparatory period (PP), lasting either 1.0, 1.5, or 2.0 s, began; PP durations were randomly ordered. The PP ended with the illumination of either the target or one of the targets adjacent either to the single LED or to one of the set of LEDs previously illuminated as a precue. These served as imperative signals. The PP duration was chosen as soon as the subject pointed at it by moving the corresponding handle, and hence the pointer, and maintained the pointers within the target for at least 200 ms. A new ITI then started, initiating the next trial. When pointers were not at the starting position at the end of the ITI or were not maintained at this position during the PP, the ITI was reset, initiating the same trial.

Experimental design. There was a large number of possible precues because of the many different arrangements and combinations of the LEDs made possible by the experimental apparatus. However, only the configurations of precues formed by 1, 2, 4, or 8 LEDs were used in the present series of experiments. The LEDs, according to their number \((N)\), supplied the subject with either complete information (when \(N = 1\)), partial information (when \(N = 2\) or 4), or no information (when \(N = 2, 4,\) or 8) about the spatial dimensions of the target to be illuminated. Thirteen conditions of precuing were thus selected, as a function of (a) the number of S-R alternatives \((N)\), (b) the number \((0, 1, 2,\) or 3\) of spatial dimensions specified by the precue, and (c) the nature (hand, direction, or extent) of the spatial dimension specified by the precue. An example of the precue configuration for each of these 13 precuing conditions is shown in Figure 2. When \(N = 1, 2, 4,\) and 8, the different types of precue configurations for each precuing condition were 8, 4, 2, and 1 respectively. Note that when \(N = 4\) and no dimension was specified in advance, there were 4 possible patterns of precue configurations, so that the total number of precue configurations used in the experimental design was 16. Finally, the total number of different trials, defined by both the precue configuration \((N = 16)\) and the target actually illuminated \((N = 8)\) was 128. In order to equate the number of trials in each precuing condition, the minimal number of trials was 192. The counterbalancing of the PP duration, as a function of the precue configuration and target actually illuminated, was achieved over these 192 trials. This resulted in an experimental session subdivided into three series of 64 trials separated by a 10-min rest period. Trials were randomly presented by using a...
**Examples of Precue Configurations in Each Condition**

<table>
<thead>
<tr>
<th>Number of Alternatives</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions specified by the precue</td>
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<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>O O O</td>
<td>O O O</td>
<td>O O O</td>
<td>O O O</td>
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<tr>
<td></td>
<td>Hand</td>
<td>Direction</td>
<td>Extent</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>O O O</td>
<td>O O O</td>
<td>O O O</td>
<td>O O O</td>
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<tr>
<td></td>
<td>Hand</td>
<td>Direction</td>
<td>Extent</td>
<td></td>
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<tr>
<td>4</td>
<td>O O O</td>
<td>O O O</td>
<td>O O O</td>
<td>O O O</td>
</tr>
<tr>
<td></td>
<td>Hand</td>
<td>Direction</td>
<td>Extent</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>O O O</td>
<td>O O O</td>
<td>O O O</td>
<td>O O O</td>
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<tr>
<td></td>
<td>Hand</td>
<td>Direction</td>
<td>Extent</td>
<td></td>
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</tbody>
</table>

Figure 2. Examples of the light-emitting diode configurations presented as precues in the different precuing conditions in Experiment 1.

computer program for sampling without replacement. Each subject performed one training session, followed by three daily experimental sessions separated by a few days.

**Data analysis.** Valid inferences about the timing of programming processes can be drawn from the changes in RT according to precuing conditions, provided that there were no associated changes in movement time (MT), that is, in the timing of execution processes. Both RT (the time between target illumination and onset of pointer movement) and MT (the time between onset of pointer movement and the target achievement) were therefore recorded for each trial. When an error in the hand used or the direction of movement occurred (which was rare after training), the trial was thrown back into the pool of subsequent trials. RT and MT were obtained only after the subject accurately pointed at the target, possibly after the subject had crossed the target and come back on it. No error score was therefore computed. Subjects did not receive feedback about their performance.

In a first stage of the statistical analysis, the effects of the number of alternatives and precued dimensions were evaluated by using the multiple regression method applied to both RT and MT data. In a second stage, a set of independent F tests of significance was made in the following way: Consider a set of k overall means related to the levels of a fixed-effect variable, C. Provided a table of S (subjects, as random-effects variables) × C individual means, the overall main effect of C can be tested through the ratio of the mean square for C and the mean square for the interaction S × C, with k - 1 and (k - 1) × (S - 1) degrees of freedom. So, here we selected a set of orthogonal partial comparisons (chosen for their specific appropriateness in relation to the hypotheses discussed), among the overall RT means for the 13 precuing conditions. For every such comparison we computed the S × C corresponding table of individual means, and the F test followed, with (k - 1) and (k - 1) × 19 degrees of freedom.

**Results**

**Reaction time analysis.** The mean RTs in the different precuing conditions are shown in Table 1 as a function of the dimension values that were either precued or remained to be specified. Differences in RT between the dimension values when each dimension was either precued or remained to be specified, either alone or with the other dimensions, are shown in Table 2.

The multiple regression analysis of RT as a function of the number of alternatives (expressed in bits) and cueing hand, direction, or extent, resulted in the following regression equation: RT = 414.63 ms (baseline without precue), -21.45 ms (per bit) - 11.91 ms (for cuing hand) - 12.79 ms (for cuing direction) - 10.33 ms (for cuing extent). The multiple correlation test (R = .424) was statistically significant, F(4, 255) = 14.02, p < .001.

Given these overall results, the effects on RT of dimensional information provided by the precue were analyzed in an analysis of variance (ANOVA), at each level of S - R uncertainty.

When N = 2, the RTs observed in the 7 precuing conditions (3two precued dimension conditions, 3 one precued dimension conditions, and 1 no precued dimension condition) were significantly different, F(6, 114) = 9.79, p < .001. They were significantly shorter when two dimensions were precued (355 ms) than when either one dimension (366 ms) or no dimension (364 ms) was precued, F(1, 19) = 24.00, p < .001. However, RTs in these latter two conditions did not significantly differ, F(1, 19) = 2.30, p > .10. When two dimensions were precued, RTs observed when either the hand (356 ms), movement direction (349 ms), or movement extent (360 ms) remained to be specified differed significantly, F(2, 38) = 5.20, p < .01. However, when only one dimension was precued, RTs did not significantly differ according to the precued dimension, F(2, 38) = 2.62, p > .05.

When N = 4, the RTs observed in the 7 precuing conditions (3 one precued dimension conditions and 4 no precued dimension conditions) were significantly different, F(6, 114) = 3.81, p < .005. They were significantly shorter when one dimension (384 ms) was precued than when no dimension (391 ms) was precued, F(1, 19) = 13.93, p < .005. However, in conditions where one dimension was precued, RTs did not differ according to the precued dimension, F(2, 38) < 1.

When the corresponding dimension remained to be specified, either alone or with the other dimensions, mean RTs were shorter (but not significantly) for left-hand than for right-hand movements, shorter for extension than for flexion movements, F(1, 19) = 10.11, p < .005, and shorter for long extent than for short extent movements, F(1, 19) = 34.01, p < .001.
Table 1

*Reaction Times and Movement Times of Experiment 1 and Reaction Times of Experiment 2 for the Precuing Conditions (in Milliseconds)*

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<th>No. of alternatives</th>
<th>No. of precued dimensions</th>
<th>Precued dimensions</th>
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<th>Left</th>
<th>Extension</th>
<th>Flexion</th>
<th>Short</th>
<th>Long</th>
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<tr>
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<td>H, D, E</td>
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<td>294</td>
<td>292</td>
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<td>296</td>
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<tr>
<td>2</td>
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<td>H, D</td>
<td>355</td>
<td>344</td>
<td>356</td>
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<td></td>
<td>2</td>
<td>D, E</td>
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<td><strong>Experiment 2: Reaction time</strong></td>
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<td>542</td>
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<td>(693)</td>
<td>696</td>
<td>(686</td>
<td>703</td>
<td>695</td>
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</tbody>
</table>

*Note.* Data not in parentheses for Dimension were precued, and those in parentheses were to be specified by the subjects' responses. H = hand; D = direction; E = extent; S = side; L = vertical location; and D = distance.
Table 1

Differences in Reaction Time (in Milliseconds) Between Dimension Values for Experiment 1 and Experiment 2

<table>
<thead>
<tr>
<th>Dimension condition</th>
<th>Hand</th>
<th>Direction</th>
<th>Extent</th>
</tr>
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<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td>To be specified</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alone</td>
<td>359.0</td>
<td>352.0</td>
<td>7.0</td>
</tr>
<tr>
<td>With other dimensions</td>
<td>382.0</td>
<td>376.0</td>
<td>6.0</td>
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<tr>
<td>M</td>
<td>370.5</td>
<td>364.0</td>
<td>6.5</td>
</tr>
<tr>
<td>Precued</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alone</td>
<td>379.0</td>
<td>371.0</td>
<td>8.0</td>
</tr>
<tr>
<td>With other dimensions</td>
<td>339.0</td>
<td>331.0</td>
<td>8.0</td>
</tr>
<tr>
<td>M</td>
<td>359.0</td>
<td>351.0</td>
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</tr>
<tr>
<td>To be respecified</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alone</td>
<td>433.0</td>
<td>431.0</td>
<td>2.0</td>
</tr>
<tr>
<td>With other dimensions</td>
<td>440.0</td>
<td>436.0</td>
<td>4.0</td>
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<tr>
<td>M</td>
<td>436.5</td>
<td>433.5</td>
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</tr>
<tr>
<td>Primed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alone</td>
<td>436.0</td>
<td>446.0</td>
<td>-10.0</td>
</tr>
<tr>
<td>With other dimensions</td>
<td>394.0</td>
<td>393.0</td>
<td>1.0</td>
</tr>
<tr>
<td>M</td>
<td>415.0</td>
<td>419.0</td>
<td>-4.0</td>
</tr>
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</table>

was reversed (statistically): mean RTs for left-hand movements became significantly shorter than for right-hand ones, $F(1, 19) = 7.27, p < .025$, whereas differences between dimension values disappeared for movement direction, $F(1, 19) = 1.81, p > .10$, as well as for movement extent, $F(1, 19) = 2.76, p < .10$.

Movement time analysis. The mean MTs in the different precuing conditions are shown in Table 1 as a function of the dimension values that either were precued or remained to be specified.

The multiple regression analysis of MT gave the following regression equation: $MT = 107.11$ ms (baseline without precue) + $1.45$ ms (per bit) + $0.69$ ms (for cuing hand) + $2.57$ ms (for cuing direction) - $4.74$ ms (for cuing extent). The multiple correlation test ($R = .108$) was not statistically significant, $F(4, 255) = 0.757$. This shows that there was no effect of both the level of uncertainty and the precued dimensions on the mean MT.

In particular, MTs observed in conditions where either one or two dimensions were precued did not differ from conditions in which no dimensional information was provided, $F(1, 19) < 1$, when $N = 2$, and $F(1, 19) = 3.51, p > .05$, when $N = 4$.

Finally, the mean MTs were significantly shorter for extension than for flexion movements, $F(1, 19) = 5.05, p < .05$, when the direction remained to be specified, and $F(1, 19) = 4.67, p < .05$, when it was precued, and for long extent than for short extent movements, $F(1, 19) = 113.98, p < .001$, when the extent remained to be specified, and $F(1, 19) = 63.87, p < .001$, when it was precued. No consistent difference in MT between left-hand and right-hand movements was found, $F(1, 19) = 2.51, p < .10$, and $F(1, 19) < 1$.

Discussion

The validity of drawing inferences from RT is established because there were no changes in MT as a function of the number either of S-R alternatives or of precuing conditions. The effects of manipulating S-R uncertainty and advance information about movement dimensions did not affect processes responsible for movement execution but rather processes taking place before movement started and, thus, were selectively expressed in RT changes.

The analyses showed that RT changes observed in both sets of precuing conditions in which the number of S-R alternatives was fixed resulted from changes in the amount of information provided by the precue about movement spatial dimensions. Insofar as the S-R compatibility in our experimental setup was high (perhaps the highest possible because precuing signals, imperative signals, and targets were spatially superimposed), these data clearly disagree with Goodman and Kelso's (1980) conclusion that significant effects of precuing movement parameters can be observed only in low-compatibility conditions, a conclusion that was recently drawn also by Zelaznik and Hahn (1985).

When the number of S-R alternatives was 2, differences in MT between the precuing conditions in which two movement dimensions were specified in advance can be interpreted as the specification time of the third uncued movement dimension. These differences show that the time needed for specifying movement extent was shorter than the time needed for specifying direction or hand. However, although this conclusion is similar to that drawn by Rosenbaum (1980) and by Larish and Frekany (1985) from their data, it cannot be viewed as generally the case because the difference between...
dimension values cannot be evaluated on a scale common to the three movement dimensions. Note especially that in our experimental setup, as well as in Rosenbaum’s and Larish and Frekany’s, hand and movement direction were binary discrete dimensions, whereas movement extent was a continuous dimension. The “long” and “short” values that were arbitrarily chosen on this dimension could not be as contrasted as were the values for hand and movement direction. These differential features of movement dimensions are likely a sufficient explanation for the shortest RTs always being found in the precuing conditions where only movement extent remained to be specified. In contrast, specification time for either binary discrete dimension was found to be longer for hand than for movement direction (Rosenbaum, 1980), longer for movement direction than for hand (Larish & Frekany, 1985), or not significantly different for either dimension, as in our experiment.

When the number of S-R alternatives was 2 but only one movement dimension was specified in advance, the mean RTs did not differ significantly from RTs observed when no movement dimension was specified in advance, a finding that can be also observed in Larish and Frekany’s (1985) data. We suggest that when a single dimension has been specified in advance and the choice between the remaining combinations of two dimensions is itself reduced to two alternatives, some “dimensional reduction” may take place in the programming of these two dimensions. Recall that three binary dimensions generate a set of eight potential alternatives. By specifying just one of these dimensions the set of potential alternatives may be reduced to either four whose dimensional values are independent or two alternatives with highly correlated values on the two remaining dimensions. For example, consider the case in which extent is the precued dimension and “long” is the value chosen to be precued. The precue signal on the display can include either all four “long” alternatives or just the upper left and lower right. In either case, hand and direction remain to be specified. However, in the first case hand and direction may be specified independently, whereas in the second case, upper left and lower right are the only two permissible alternatives; specifying the value of either dimension therefore determines the value of the other. We suggest that this correlational structure is of considerable help in reducing the subject’s processing load.

RT data collected with the precuing technique may also provide some insight into the structure of the programming process, that is, about the validity of a model in which the programming operations for the different dimensions are serially organized. A serial programming model of movement dimensions implies that the programming time component of RT must be an additive function of the number of dimensions to be specified. However, it must be emphasized that a finding that the observed variable, RT, is additive is not sufficient for concluding that programming times themselves are additive, because other RT components can also change according to dimensional precuing conditions. Similarly to interpret RT differences as Rosenbaum (1980) proposed, RT must be modeled as a sum of additive components, including a perceptual stage during which the imperative signal is identified, a programming stage during which the motor program is built and loaded, and a motor stage during which the program is translated into neuromuscular commands. Manipulation of information about movement dimensions is assumed only to act on the programming component, whereas the number of S-R alternatives is assumed to affect both the perceptual and the motor components but not the programming component.

The last assumption is, of course, important for testing the additivity of the dimension programming times. This is because the precuing technique confounds effects of the number of precued dimensions and the number of S-R alternatives on RT. Consequently, we propose two alternative strategies for examining the additivity of the dimension programming times. The first one is to proceed with an overall test of additivity over the different levels of S-R uncertainty, if the assumption of a linear relationship between RT and information rate is verified (viz., Hick’s, 1952, law). The second one is to proceed with a partial test of additivity within a set of dimensional precuing conditions that do not differ in the number of S-R alternatives. This strategy was the main justification (Goodman & Kelso, 1980; Larish & Frekany, 1985) for introducing control conditions that do not provide any information about movement dimensions, although the number of S-R alternatives remain the same as in the dimensional precuing conditions.

Within this framework it appears that whatever testing strategy is used, RT data provided by Experiment 1 do not show additivity. As for the first, overall, additivity test, RTs observed when 3, 2, 1, and 0 movement dimensions were precued for conditions in which the number of S-R alternatives was 1, 2, 4, and 8, respectively, differ from RTs predicted by the additivity model, \(F(4, 76) = 29.52, p < .001\). This does not, obviously, lead one to conclude that dimension programming times are not additive, because the underadditivity of RT data may only mean that the relationship between RT and information rate does fit Hick’s law (Hick, 1952). Indeed, Figure 3 shows that the relationship between RTs and information rate observed in conditions that did not provide any dimensional information (i.e., conditions in which the number of S-R alternatives was either 2, 4, or 8) deviates somewhat from linearity. As for the second, partial, additivity testing strategy applied to RT data for conditions in which the level of S-R uncertainty is constant, when the number of S-R alternatives was 2, no difference in RT was found between conditions in which no dimensional information was provided and conditions in which one movement dimension was precued. This finding provides sufficient evidence to reject the additivity hypothesis. The same conclusion is suggested by another finding. Differences between dimension programming times, as estimated by RT differences when each dimension remained to be specified alone, disappeared when that dimension and another one remained to be specified (see also Rosenbaum, 1980). Note that both of these latter findings are interpreted in the framework of a dimensional reduction hypothesis, that is, that when the number of movement dimensions to be specified increases, the programming operations are increasingly collapsed in some compound pro-
Figure 3. Averaged reaction time (RT) as a function of the number of alternatives, expressed as information rate, in Experiments 1 and 2. (In Experiment 1, only RTs for the precuing conditions in which no dimensional information was provided by the precue were considered. Such a selection was, of course, not possible when the number of alternatives was 1, that is, in the simple RT condition.)

cess. It can therefore be suggested that such a dimensional reduction hypothesis is one of the likely explanations of the underadditivity of dimension programming times.

Finally, the RT data collected in our experiment provide some insight into the functional nature of the precuing effects. As developed in the introduction, experimental evidence for either preprogramming or for facilitating processing due to the precue may be provided by a comparison of the differences in RT between dimension values, depending on whether the corresponding movement dimension is precued or not. For two dimensions (direction and extent), a significant difference in RT between dimension values was found when these dimensions had to be specified after the imperative signal. For direction as well as for extent, this difference in RT between dimension values disappeared when these dimensions were precued. These data therefore provide strong support for the hypothesis that the precue triggered the programming of the precued movement dimension, because the differences in RT between dimension values when these latter remained to be specified were no longer expressed in the RT when the corresponding dimension was precued.

Experiment 2

On the basis of findings from the movement–dimension precuing technique, Rosenbaum (1980) argued that the RT reductions found in the different precuing conditions could not result only from reducing the programming component of RT. In particular, he hypothesized that changes in RT could be associated, at least in part, with changes in the spatial configuration of the visual stimuli used to present the precue and imperative signals. That is, they could result from purely perceptual effects modifying the perceptual time component of RT.

To examine the role that such perceptual effects might play in the precuing effects, we designed a control experiment. The manner in which the precue and imperative signals were presented was the same as in Experiment 1. However, the response (pointing) movement was changed to one that is hardly decomposable into spatial dimensions, a vocal response. A control experiment based on this idea was previously conducted by Rosenbaum (1980; Experiment 2). However, Rosenbaum modified the design of the precuing technique. In his experiment, on half of the trials, the imperative signal was different from that announced by the precue information. In such a case, the subjects were required to say "false," whereas they had to say "true" when the precue provided appropriate information about the imperative signal. Our second experiment was differently designed. We replaced the eight LEDs that served to present the precues by eight differently colored dots in order to present the precues as well as the imperative signals. Nothing was changed in the experimental design of Experiment 1, and the subjects were now required to name the color of the imperative signal after having seen a pattern of colored dots as precue. Changes in vocal RTs as a function of the precuing conditions (possibly, as in Experiment 1, according to the spatial features of the precue) would support the hypothesis that perceptual effects intervened in the dimensional effects found in Experiment 1. In contrast, the lack of any change in vocal RTs according to dimensional precuing conditions would confirm that changes in RT found in Experiment 1 were related to the programming of movement dimensions. In this latter case vocal RTs would depend on the number of S–R alternatives only. This control experiment, therefore, provided data in conditions quite similar to those in Experiment 1 and made possible an evaluation of the relationship between RT and information rate. In turn, this might help to address the problem raised by an overall test of the programming times additivity.

Method

Subjects. Twenty right-handed subjects, 13 women and 7 men, between the ages of 20 and 40 years participated and were paid 30 francs ($5) per hr. Sixteen of them had previously participated in Experiment 1. The subjects were not informed about the aim of the experiment.

Apparatus. The apparatus used in Experiment 1 was modified as follows: A black screen was fixed on the display panel, covering over the red LEDs. Eight circular holes, 4 mm in diameter, were cut out
of this screen in front of the eight targets. Each of them was closed by a monochromatic filter to obtain a spatial pattern of eight different colored stimuli, each of which were visible when the LED behind it was illuminated. To make color naming times as equal as possible, the eight colors that were chosen have monosyllabic names starting with a consonant: bleu (blue); rouge (red); rose (pink); vert (green); jaune (yellow); mauve (violet); blanc (white); brun (brown).

To minimize the opportunity for the subject to identify colors on the basis of their spatial location only, 16 different screens were built, on which the colored filters were differently located.

A microphone connected to a vocal key was located at the level of the subject’s mouth.

Procedure. The timing of a trial was identical to that of Experiment 1. After an ITI of 4 s, a trial started with a 1-s illumination of either 1, 2, 4, or 8 colored stimuli, as a precue. After a PP of either 1.0, 1.5, or 2.0 s, the colored stimulus or one of the colored stimuli used to form the precue was illuminated again, as an imperative signal, and the subject had to name its color as quickly as possible.

Experimental design. For each subject 12 of the 16 possible spatial configurations of the eight colored stimuli were used during 12 blocks of 64 trials. Subjects participated in four daily sessions of 3 blocks each. These 12 spatial configurations were different for the 20 subjects in such a way that the 16 possible configurations were used equally within the group; the configuration was changed from one block to another and sequential effects were counterbalanced across subjects. Before the four experimental sessions, the subjects participated in one training session in order to become familiar with the colors and to practice their names.

During each session of 192 total trials (64 trials × 3 blocks) the selection and presentation order of the precuing conditions were identical to that of Experiment 1.

Data analysis. Reaction time was measured between presentation of the colored stimulus used as an imperative signal and the triggering of the vocal key by the subject’s voice. Because very few errors of naming were observed after the training session, no error score was computed. The statistical analyses in this experiment were procedurally identical to those of Experiment 1.

Results

The mean RTs in the different precuing conditions are shown in Table 1, as a function of the dimension values that were either precued or remained to be specified. One must recall that these dimensions do not refer here to the spatial dimensions of any movement but to the spatial dimensions of target location; they were therefore labeled as side, vertical location, and distance from the symmetry axes of the display panel.

The results showed that mean RTs were consistently longer (between 500 ms and 700 ms) than those observed in Experiment 1 (between 300 ms and 400 ms). Multiple regression analysis of RT data clearly demonstrated the effect on RT of the number of alternatives but not of precuing the side, vertical location, or distance. The regression equation was: RT = 745.49 msec (baseline without precue) − 106.24 ms (per bit) − 0.29 ms (for cuing side) − 7.23 ms (for cuing vertical location) − 7.52 ms (for cuing distance). The multiple correlation test (R = .626) was only significant for the number of alternatives; the increase in predictability of RT (from .625 to .626) resulting from precuing side, vertical location, or distance was not significant, F(2, 355) = .175. This overall result was confirmed by the ANOVA that was done at each level of S–R uncertainty.

When N = 2, RTs were the same in conditions in which two (532 ms) or one dimension (533 ms) was precued, F(1, 19) < 1. They were significantly shorter when no dimension (519 ms) was precued, F(1, 19) = 11.89, p < .005. However, RTs did not significantly differ according to the precued dimensions when two dimensions were precued, F(2, 38) < 1, or when one dimension was precued, F(2, 38) < 1.

When N = 4, RTs were the same in conditions in which one dimension (651 ms) or no dimension (649 ms) was precued, F(1, 19) < 1. When one dimension was precued, RTs did not differ according to the precued dimension, F(2, 38) < 1.

Finally, when the corresponding dimension remained to be specified, either alone or with the other dimensions, mean RTs were significantly shorter when the colored imperative signal was presented on the right side of the display panel than when it was presented on the left, F(1, 19) = 25.38, p < .001, and when the imperative signal was presented near rather than when it was presented far from the midhorizontal plane, F(1, 19) = 13.94, p < .005. No consistent difference in the RTs was observed when the imperative signal was presented either above or below the midhorizontal plane, F(1, 19) < 1. These differences in RT between dimensions values remain significant for distance, F(1, 19) = 6.57, p < .025, but were no longer significant for side, F(1, 19) = 3.07, p < .10, when the corresponding dimension was precued, either alone or with the other dimensions.

Discussion

The results of this control experiment do not generally support the hypothesis that the dimensional precuing effects found in Experiment 1 resulted from perceptual effects associated with changes in the precue configuration. Dimensional effects are differences in RT according, first, to the number of precued dimensions and, second, to the precued dimension when this number is constant; in addition, they include changes in the RT difference between dimension values depending on whether movement dimensions are precued. Except in one condition, to be discussed later, dimensional effects disappear when the response required from the subject cannot be decomposed any further in its spatial dimensions.

However, RTs with the precuing configurations that provided no dimensional information were always shorter than RTs with the precuing configurations that did provide information about either one or two dimensions. Although the difference in RT was statistically significant only when the number of S–R alternatives was 2, these data suggest that the unexpectedly short RTs resulted from perceptual effects. However, it is difficult to specify what the particular advantage was that these configurations of color dots had for facilitating the identification and naming of one among these dots. On the other hand, it must be emphasized that the short RTs observed in the similar no-information conditions of Experiment 1 (which were shorter than those expected according to an additive model of the dimension programming times) were the main support for the "dimensional reduction" hypothesis. It is possible, therefore, that perceptual effects in some precuing conditions of Experiment 2 explain the underadditivity effect.
of programming times found in Experiment 1. Alternatively, dimensional reduction may apply not only to the movement programming process but also, at least in part, to the signal identification process.

This last hypothesis appears especially likely because presentation of the same spatial configuration of the colored dots during a whole series of trials made it possible to decode the precue on the basis of an association between colors and spatial positions. If the subject's task in Experiment 2 was to name the color of the imperative signal by identifying its spatial position on the display panel, then the identification process may be, in part, similar to the parametric movement programming process. It is similar because the spatial location of each colored dot can be decomposed into three dimensions: its side (left vs. right), vertical location (above vs. below) and distance (small vs. large). Therefore, dimensional reduction may explain the results of Experiment 2 as well as those of Experiment 1. Thus, when the number of signal–spatial dimensions remaining to be identified increased, the unpaced spatial dimension values could be correlated (in the form, for instance, of "either below, large, and on the left or above, small, and on the right"), and the identification operations could be collapsed in some compound process. This similarity between processes intervening in identifying the imperative signal and in programming the response movement must thus be considered a consequence of the high spatial compatibility between the precue and target configurations, both being decomposable in quite similar (spatially isomorphous) binary dimensions. This leads us to suggest that the additivity of dimension programming times ought to decrease when spatial S–R compatibility increases. This is in line with claims by Goodman and Kelso (1980).

Because vocal RT did not change according to the dimensional prepping conditions, the data collected in this second experiment were thus appropriate for examining the relationship between RT and the number of S–R alternatives in conditions quite similar to those of Experiment 1. Such a relationship is shown in Figure 3. In the figure the number of S–R alternatives are transformed into information rate. It appears clearly that the RT–information rate relationship was not linear and, therefore, did not conform Hick's (1952) law. This adds to evidence drawn from Experiment 1 that the necessary condition for verifying the additivity of programming times over the entire set of RT data (viz., over the different uncertainty levels) was not verified in the prepping paradigm, at least in the experimental setup that we adopted.

Experiment 3

Taken together, the results of Experiments 1 and 2 lead us to somewhat ambiguous conclusions about the parametric or dimensional conception of movement programming. On one hand, three findings support the hypothesis that the programming of movement dimensions may result from the assembly of independent, at least separable, operations. First, when two dimensions were precued, RTs were shorter than when only one dimension was precued; second, this RT shortening was found for all pairs of precued dimensions; third, this RT shortening differed according to the dimension that remained to be programmed. On the other hand, this set of RT data does not confirm a serial processing model of movement programming operations, whatever the method used for testing additivity. In contrast, some aspects of the results appear compatible with the hypothesis of a dimensional reduction process, according to which the programming of movement dimensions is integrated in a compound operation as soon as more than one movement dimension remains to be programmed. However, the role played by such a compound process so that RTs are underadditive must be quite complex, because it can intervene not only in the programming of movement dimensions but also in the identification of the spatial features of the precue and imperative signals, at least with a high spatial compatibility between precues and targets.

Finally, the analysis of RT differences between dimension values depending on whether movement dimensions are precued or not suggest that dimensional information provided by the precue is used to program the precued dimensions in advance and not to facilitate the programming process after the imperative signal has occurred. This suggests our preprocessing notion.

However, these preliminary conclusions are supported by small (and sometimes nonsignificant) differences between RTs found in the prepping conditions and RTs expected from a serial processing model of programming operations. Furthermore, these conclusions are based on small (and sometimes nonsignificant) differences between the programming times for the different movement dimensions, according to the number of precued dimensions. As emphasized in the introduction, the principles underlying the priming technique led us to predict an amplification of the dimensional prepping effects if deprogramming and reprogramming times of movement dimensions are added. Therefore this priming technique offered a convenient experimental strategy not only to confirm results of Experiment 1 but also to provide a set of data supporting the hypothesis of a dimensional reduction programmes process. This use of the priming technique is extended in Experiment 3.

Method

Subjects. Twenty right-handed subjects, 12 women and 8 men, between the ages of 20 and 40 years participated for payment of 30 francs ($5) per hr. Sixteen of the subjects had previously participated in Experiment 2, and 12 in Experiment 1. They were not informed about the purpose of the experiment.

Apparatus. The apparatus was exactly the same as in Experiment 1.

Procedure. The pointing task, performed under the temporal constraints of the RT procedures, and the timing of a trial were identical to those in Experiment 1. The configuration of the precue and the rule for associating the prime and the imperative signal were modified. In this experiment the precue was a single red LED serving as a prime. The imperative signal was either adjacent to the prime or it was nonadjacent.

Experimental design. In each block of 160 trials, the prime was valid on 65% of trials. On these trials the imperative signal was an illuminated target adjacent to the precue. The prime was invalid on 35% of trials. On these trials, the imperative signal was the illumination of one of the seven other targets. These 160 trials were randomly
presented according to a computer program of sampling without replacement. Each experimental session comprised two blocks, and each subject participated in one training session followed by three daily experimental sessions.

In order to encourage the subject to prepare to point at the target adjacent to the prime, the subject was instructed that the only efficient strategy was to prepare as if the target adjacent to the prime had always to be pointed at. However, in order to check how such an instruction interacted with the usual frequency effect on RT, the prime was always valid in one block of trials of the last session. A comparison of RTs observed after primes that are valid on either 65% or 100% of trials was therefore made possible in this session. The order of these two blocks of trials was counterbalanced within the group of subjects.

Data analysis. The RT and MT were recorded for each trial. The statistical analyses in this experiment were procedurally identical to those of Experiments 1 and 2.

Results

Reaction time analysis. Table 3 shows the mean RTs as a function of the number and nature of the spatial dimensions that the primed and the actually performed pointing movements had in common (referred to as the primed dimensions). Data of the two blocks of the last session, in which the probabilities that the prime was valid were .65 and 1.00, respectively, were separately analyzed. Differences in RT between dimension values when each dimension was either primed validly or had to be respecified, either alone or with the other dimensions, are shown in Table 2.

The results show that RT was a decreasing function of the probability that the prime was valid. The mean RT difference (90 ms) when the prime was invalid (433 ms) and valid (343 ms) is highly significant, F(1, 19) = 190.70, p < .001. In the last session, the mean difference in RT (37 ms) between conditions in which the probabilities were .65 and 1.00, respectively, is highly significant, F(1, 19) = 47.00, p < .001. Note that the mean RT observed in this latter case (297 ms) was the same as that observed in the analogous condition of Experiment 1 (296 ms), that is, when N = 1.

Although there was no difference in RT between conditions in which no dimension (438 ms) or one dimension (439 ms) was primed validly, the RT difference of 16 ms between conditions in which one and two dimensions (423 ms) were primed validly is highly significant, F(1, 19) = 37.55, p < .001.

Furthermore, when the hand and direction were primed validly and movement extent had to be respecified, RTs were significantly shorter (432 ms) than when either hand (432 ms) or movement direction (439 ms) had to be respecified F(I, 19) = 47.04, p < .001. Reaction times observed in these latter two conditions did not differ, F(I, 19) = 3.46, p < .10. However, when one dimension, movement extent, was

<table>
<thead>
<tr>
<th>No. of primed dimensions</th>
<th>Primed dimensions</th>
<th>Right</th>
<th>Left</th>
<th>Extension</th>
<th>Flexion</th>
<th>Short</th>
<th>Long</th>
<th>M</th>
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<tr>
<td>3</td>
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<td>339</td>
<td>342</td>
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<tr>
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<td>H, D</td>
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<td>405</td>
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<td>399</td>
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<td>2</td>
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<tr>
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Note. Data not in parentheses for Dimension were primed, and those in parentheses were to be specified by the subjects' responses. H = hand; D = direction, and E = extent.

Table 3

Reaction Times and Movement Times of Experiment 3 for the Priming Conditions (in Milliseconds)
primed validly (432 ms) RTs were significantly shorter than when either hand (441 ms) or movement direction (443 ms) was primed validly, \(F(1, 19) = 30.00, p < .001\). Reaction times observed in these latter two conditions did not differ, \(F(1, 19) < 1\).

Dimensional effects on RT were expected to depend on the amount of preparation for the primed movement (although the probability that this movement would have to be performed was .65). Therefore, supplementary analysis of RTs was done to test this expectation. Two subgroups of subjects were selected on the basis of two criteria. When the prime was valid, mean RT served as an index of the amount of general preparation or involvement in the task. The difference in RT between the two blocks of the last session (in which the probabilities that the prime was valid were .65 and 1.00, respectively) served as an index of the amount of specific preparation for the primed movement. Fortunately, it appeared that 5 subjects were both fastest (shortest mean RTs) and best prepared (weakest RT difference between the two blocks of the last session), and 5 other subjects were both slowest and least prepared. Mean RTs observed for these two subgroups of subjects are shown in Figure 4 as a function of the number and nature of the primed dimensions.

Reaction times for conditions in which two dimensions were primed validly and where one dimension was primed validly did not differ significantly for the fastest and best prepared or for the slowest and worst prepared subjects, \(F(1, 4) = 2.82, p < .10\). When two dimensions were primed validly, dimensional effects (that is, the RT difference between conditions in which movement extent had to be respecified and where either the hand or movement direction had to be respecified) were consistently larger for the fastest and best prepared than for the slowest and worst prepared subjects, \(F(1, 4) = 12.04, p < .05\). However, when one dimension was primed validly, RT differences according to the primed dimension were significantly larger for the slowest and worst prepared subjects than for the fastest and best prepared subjects, \(F(1, 4) = 8.00, p < .05\).

Furthermore, when dimensions had to be respecified, mean RTs for the whole group of subjects were significantly shorter for large-extent than for short-extent movements, \(F(1, 19) = 20.97, p < .001\). They did not differ significantly between left-hand and right-hand movements, \(F(1, 19) < 1\), or between extension and flexion movements, \(F(1, 19) < 1\). The RT difference between extent values disappeared when movement extent was primed validly, \(F(1, 19) < 1\).

Finally, no consistent changes in these RT differences between dimension values were found when each dimension had to be respecified, either alone or together with the other dimensions.

Movement time analysis. Table 3 shows the mean MTs in the different priming conditions as a function of the dimension values that either were primed validly or had to be respecified.

Mean MTs were significantly shorter when the prime was valid than when the prime was invalid, \(F(1, 19) = 33.18, p < .001\). Moreover, in conditions where the prime was invalid, mean MTs were significantly longer when two dimensions were primed, \(F(1, 19) = 8.88, p < .01\).

Finally, when dimensions had to be respecified, mean MTs were significantly shorter for large-extent than for short-extent movements, \(F(1, 19) = 53.73, p < .001\), for right-hand than for left-hand movements, \(F(1, 19) = 7.61, p < .05\), and for extension than for flexion movements, \(F(1, 19) = 5.15, p < .05\). The large MT difference observed for movement extent values did not change when this dimension was primed validly, \(F(1, 19) < 1\).

Discussion

As expected, the results of this priming experiment confirmed those of the precuing experiment by amplifying the main dimensional effects previously found. First, RT depended on the number of primed dimensions, being shorter when two dimensions were primed than when one dimension was primed. Second, RT depended on the dimensions that had to be deprogrammed and reprogrammed, being shorter in particular when movement extent had to be reprogrammed alone. The amplification of the RT differences in this experiment as compared with those in Experiment 1 may be...
interpreted in the framework of the hypothesis that in the priming technique the programming system has to deprogram the movement dimensions for which the prime is invalid before deprogramming them. A comparison of the results found in this priming experiment with those in the precuing experiment when the number of S–R alternatives was 2 (cf. Figure 5), clearly reveals this very similar pattern of RT data. The magnitude of the priming effects is, of course, increased when the data collected only on subjects who can be supposed to prepare all the dimensions of the primed movement are considered. Moreover, results of this priming experiment confirm inferences drawn from the precuing experiment about the nature of the processes triggered by providing advance dimensional information. That is, when a RT difference between the unprimed dimension values was observed, which thereby allowed a difference between programming times for dimension values to be inferred, this difference disappeared when the dimension values were primed. This supports the hypothesis that the corresponding programming process took place before the imperative signal occurred.

Taken together, this set of results is in agreement with the simplest version of the parametric conception of movement programming. Providing partial advance information about movement parameters can be used by the programming system to partially program the intended movement.

However, two unexpected results of Experiment 1, which do not support a serial processing model of dimensional programming operations, were clearly found again. First, RTs were not shorter when one dimension was primed than when no dimension was primed. Second, when only one dimension was primed, the shortest RTs were found when movement extent was primed; however when two movement dimensions were primed, the shortest RTs were found when movement extent had to be reprogrammed. Both of these findings are based on statistically well-established data, yet they disconfirm that programming times are additive as a serial processing model implies. However, they support, as an alternative model, the hypothesis of a dimensional reduction process. This model proposes that when either two or all movement dimensions were not primed and thus had to be deprogrammed and then reprogrammed, a correlation or association among unprimed dimension values made a compound programming process possible.

This alternative hypothesis is sufficient to explain the underadditivity of programming times as well as the discrepancies found in dimension programming times themselves, especially when movement extent is considered. First, the greater the number of dimensions to be simultaneously programmed, the greater the efficiency of the compound programming process and, consequently, the larger the departure of the observed programming time from that predicted by a serial processing model. Second, because movement extent is not a binary discrete dimension but rather is continuous, the shortest programming time was found when extent remained to be reprogrammed alone. However when only one dimension was primed, the shortest RTs were found when the two binary discrete dimensions had to be reprogrammed (i.e., when extent was primed alone). This is because the correlation between dimension values appears to be more difficult to achieve where extent is concerned.

General Discussion and Conclusions

The finding that changes in RT differences were observed between dimension values depending on whether or not they were specified in advance is important because it supports the main assumption of the Rosenbaum's original model (Rosenbaum, 1980, 1983). Rosenbaum proposed that to precue or to prime movement dimensions would result merely in transferring some of the functions usually devoted to the imperative signal. Thus, inferences about dimension specification times are based on the principle of processing times being exchanged between the operations triggered by either signals. The theoretical implications of such a preprocessing conception have been discussed elsewhere (cf. Requin, 1985) within the framework of an information-processing stage model. This is an alternative to a presetting conception in which changes in RT result from

![Figure 5. Comparison of the reaction time (RT) data for the precuing technique (Experiment 1) and the priming technique (Experiment 3). (RTs are plotted for the precued, primed movement dimensions as a function of the number of precued, primed movement dimensions. For the precuing technique, only the RT data for conditions in which the number of alternatives was 1 or 2 are presented. H = hand; D = direction; and E = extent.)](image_url)
some facilitatory process increasing the efficiency of the programming system before it operates. Although the assumption that preparation is processing in advance (i.e., that to "specify" is to program) is not needed to predict the pattern of findings in this set of experiments, this assumption is necessary to draw inferences from these data about the order of programming operations. In contrast, in a presetting conception a facilitatory effect of precuing one dimension could be observed whatever the order of dimensional programming operations. Unfortunately, such a discussion is of limited interest because the results do not support (as we argue later) a serial processing model of motor programming in any way and, a fortiori, a fixed order of dimension programming operations.

The second conclusion of this set of experiments is related to the debate initiated by Rosenbaum (1980) and Goodman and Kelso (1980) about the role played by S–R spatial compatibility in the analysis of the movement dimension effects that can be observed with the precuing technique. Although it can be argued that in our experimental setup the subject did not have to perform a true pointing task because there was no limb displacement to reach the target, there is no serious reason to question the high S–R spatial compatibility that resulted from superimposing precue, imperative signal, and target locations. In such conditions it appears that changes in RT cannot be explained by uncertainty effects only but result in part from manipulating the amount and nature of information provided about movement dimensions. In contrast to what Goodman and Kelso (1980) and, then, Zelaznik and Hahn (1985) claimed, significant effects of precuing movement parameters can therefore be observed not only in low- but also in high-compatible conditions. Such a conclusion is, a fortiori, true when data provided by the priming technique, which amplified the dimensional effects found with the precuing technique, are considered.

However, there is some evidence that S–R compatibility may affect the movement programming process. In particular, the RT differences related to the number and the nature of precued dimensions were larger in Rosenbaum’s (1980) experiment than in Larish and Frekany’s (1985) and larger in these latter than in our results. This means that a part of the dimensional effects observed could intervene at the level of the coding of information given by the precue. A supplementary argument for such a role played by S–R compatibility is provided by the results of Experiment 2 showing that perceptual effects may explain in part the RT differences observed between precuing conditions. They suggest that, even in highly compatible conditions, it is likely that the translation process between spatial dimensions of the task (i.e., the decoding of information given by the precue about target location or the coding of the aiming action) is, before any movement programming starts, a target for the dimensional effects found with the precuing technique. It may be of interest for further investigations in this regard to be designed so that the level of S–R compatibility can be selectively manipulated. For instance, in our experimental setup we must require the subject to reverse the meaning of up and down. In this way we could study the effect of decreasing S–R compatibility on RT changes associated with the precuing of movement direction (and possibly of the other dimensions as well) in order to specify the part played by response selection and movement programming as the sites for dimensional precuing effects.

The last important point is that the results do not confirm a serial model of programming processes. Dimension specification times were never found to be additive but were clearly underadditive. Several aspects of these data suggest that the underadditivity can be explained by a dimensional reduction process. Such a compound programming process is an alternative to parallel, serial-parallel, or cascade models that the underadditivity of RTs suggests within the framework of a parametric conception of movement programming. However, it appears difficult to decide whether this alternative model remains compatible with such a parametric conception or must be considered as one of the possible mechanisms underlying a holistic conception. The programming process must still be based on the coding of the different dimension values (which can be viewed as the first step of any parameterization process). These dimension values are then compounded in a process after which movement dimensions are not separable any longer. In such a case the output of this latter assembling operation can serve to specify a unique feature of movement (for instance some neuromuscular state corresponding to the final location of the limb to be moved). This is one of the possible versions of a holistic programming conception. In other words, what may be called parametric is the coding process of spatial dimensions of the precue or of the corresponding movement, and what may be called holistic is the motor program after being assembled.

On the other hand, some aspects of our data that have led us to propose a dimensional reduction explanation suggest that further investigations are needed to verify the hypothesized programming process. Basically the idea is that the discrepancies found in dimension specification times, according to the number and nature of the dimensions that remained to be programmed, resulted from the heterogeneity of movement dimensions themselves, the hand used being necessarily discrete, direction being rendered arbitrarily discrete, and extent being necessarily continuous. The degree to which a dimensional reduction process intervenes depends directly on this heterogeneity of the movement dimensions to be programmed. Thus, specification times are more additive when movement dimensions are continuous than when they are binary discrete, because dimension values are less easily correlated, and consequently, dimension reduction is achieved less efficiently. It may be of interest to verify such a prediction by comparing the additivity of specification times in two precuing or priming conditions in which only two movement dimensions are precued or primed. For example, in the first one, advance information may be provided or not about the active arm or movement direction of monarticular movements, both dimensions being thus discrete; in the second one, advance information may be provided or not about movement direction or amplitude of polyarticular movements, that is, when direction can be defined in terms of angular direction on a plane, both dimensions being thus continuous.

In conclusion, the remaining uncertainty about the functional features of the programming system makes it necessary to take with caution any conclusion drawn from results pro-
vided by the precuing and priming techniques which are in many ways very artificial laboratory situations. In real life, persons do not usually receive prior information about the movement they intend to perform in a manner similar to that used in the frame of the advance information paradigm. We generally know what we have to do, and the main source of uncertainty is the timing needed to perform an adequate movement for reaching the goal. Movement features are therefore most often simultaneously and not successively planned. According to our hypothesis of a dimensional reduction, movement programming may thus generally result from a unitary process compounding movement features and not (except in the frame of the laboratory) from a process adding or integrating units of dimensional information sequentially delivered in time.

References


