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Choice and stimulus–response compatibility affect duration of response selection

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Abstract

In general, for movements to visual targets, response times increase with the number of possible response choices. However, this rule only seems to hold when an incompatibility exists between the stimulus and response, and is absent when stimulus and response are highly compatible (e.g., when reaching toward the location of the stimulus). Stimulus–response (S–R) compatibility can be manipulated either at the level of stimulus and response characteristics, or at the level of the mapping between elements of the stimulus and response sets. The current study was undertaken to determine the extent of the interaction between choice and each of these two levels of S–R compatibility. Subjects used a joystick to move a cursor in response to two, four or eight possible cues, with S–R compatibility manipulated along two dimensions (type of stimulus, and mapping between stimulus and response sets) in separate blocks of trials. Choice effects were absent when S–R relationships were highly compatible, moderate when incompatible in either of the two dimensions, and greatest when incompatible in both dimensions. These results indicate that choice affects response selection at each stage in the decoding of S–R relationships. Similar but smaller effects were seen for trials in which the stimulus was the same as that presented in the immediately preceding trial, suggesting that repeated stimulus–response transformations are faster and more efficient due to the priming effects of previous trials. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

A number of factors affect the time required to begin a movement in response to a stimulus. One of these is the compatibility between the triggering stimulus and the appropriate motor response [7,14]. Thus, a reaching movement will have a relatively fast response time if it is made toward the spatial location of a suddenly appearing target. On the other hand, the initiation of a similar movement will take longer when the color rather than the position of the stimulus indicates the appropriate direction of movement. This effect is not due to any particular characteristic of either the stimulus or the response, but is instead due to the degree of stimulus–response (S–R) compatibility inherent in a given task [6]. As demonstrated by Fitts and Deininger [6], the degree of S–R compatibility characterizing a task can be affected at two separate conceptual levels. First, S–R compatibility depends on the congruence of the stimulus and response characteristics; this level of S–R compatibility has been described by Kornblum et al. [14] as the ‘dimensional overlap’ of the S–R pair. Thus, some S–R combinations (e.g., spatial stimulus/spatial response: ‘press the button that illuminates’) are more compatible than others (e.g., symbolic stimulus/spatial response: ‘press the right button if a central stimulus is red, the left if green’). Second, S–R compatibility depends on the congruence of the mapping between the elements of the stimulus and response sets. For example, a task having congruent stimulus and response characteristics (e.g., both spatial) can have an incompatible mapping between the stimulus and response sets (e.g., ‘press the left button when the right one illuminates, and vice versa’).

A second factor known to affect response time is uncertainty. With larger sets of possible S–R pairs, each individual stimulus becomes less likely to be presented and

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response times increase correspondingly [11,12]. This suggests that the appropriate response to a given stimulus must be determined by a search of the set of alternatives, with longer searches necessary for larger S–R sets [14,19,21]. However, the effects of choice number and S–R compatibility are not independent. Instead, they show a strong interaction, with little or no effect of choice when stimulus and response are highly compatible [1,4,5,8,15,17]. From this observation, some investigators have suggested that under conditions of a high degree of S–R compatibility, no search of the response set is required because the appropriate response is either automatically activated by the stimulus [14,19,21] or can be determined by the implementation of a simple rule [10].

As Sternberg [20] has demonstrated, an examination of the behavioral effects of various task parameters can provide important information about the relative processing stages affected by each parameter. The current investigation was undertaken to further characterize the relationship between choice and S–R compatibility in this manner. In particular, we sought to determine if the interaction between choice and S–R compatibility acts at the level of the congruence between stimulus and response characteristics, the mapping between stimulus and response sets, or both. Subjects were required to make a movement toward a spatial goal under conditions that were varied, in blocks of trials, along three dimensions. In the ‘choice’ dimension, the number of possible targets was two, four or eight. In the ‘cue’ dimension, the stimulus was either a *spatial* cue directly indicating a location or a *symbolic* cue indicating the compass direction of the appropriate movement. In the ‘mapping’ dimension, the movement was to be directed either *toward* the indicated location or direction, or rotated 90° *counter-clockwise (ccw)*. Given the variations along the cue and mapping dimensions, the task can be described as having three levels of S–R compatibility: high (spatial/toward), intermediate (symbolic/toward and spatial/ccw) and low (symbolic/ccw).

2. Materials and methods

Eight right-handed healthy subjects (four men, four women; mean age 27.75 ± 9.7 years) agreed to participate in the study approved by the University of Minnesota Institutional Review Board, and signed informed consent forms. Subjects used a joystick to control the position of a cursor on a computer screen. In the most basic type of trial (spatial/toward/eight-choice, see below), the monitor displayed a central circle (6-mm radius) surrounded by a larger outer circle (60-mm radius) on which eight target positions were indicated by annuli (9-mm radius) positioned at 45° intervals (Fig. 1). To begin each trial, the subject moved the cursor into the central circle. After a delay of 500 ms, a filled circle replaced one of the target annuli. Subjects were required to move the cursor quickly

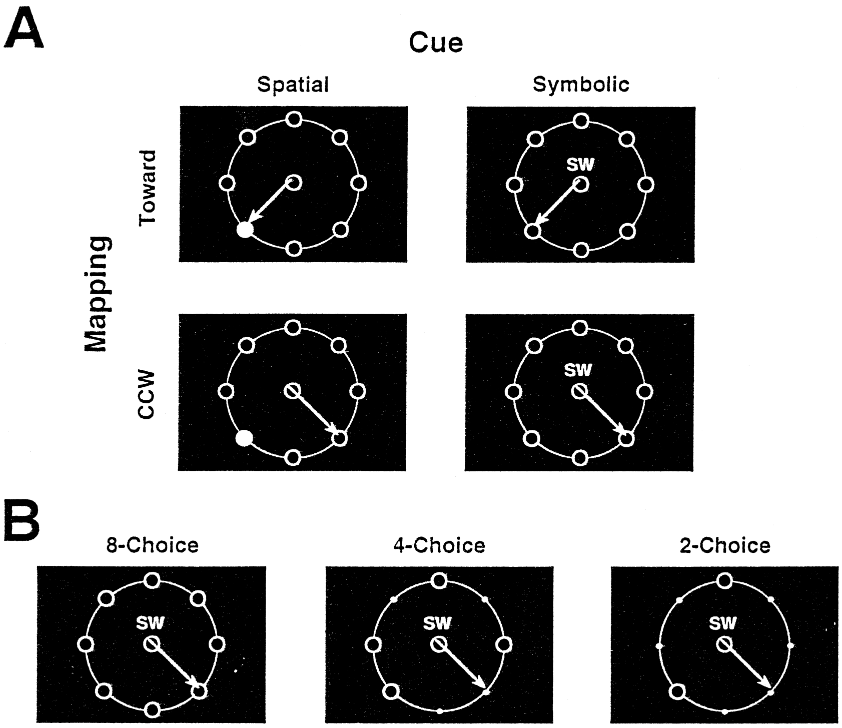

Fig. 1. (A) Schematic demonstrating the task variations in cue (spatial or symbolic) and mapping (toward or ccw). Small circles represent possible target locations; filled circles and abbreviated compass directions depict the cue in the spatial and symbolic conditions, respectively; arrows represent the movement of the cursor for a correct response in the depicted trials. (B) Schematic demonstrating the two, four and eight-choice symbolic/ccw conditions.

and accurately in the direction of the target (i.e., with an angular error of less than 22.5°) and with a minimum amplitude equal to the radius of the outer circle. Trials of a particular type were run in blocks, with subjects performing as many self-paced trials as necessary to achieve 40 correct responses. In addition to this most basic type of trial, subjects also performed 11 variations that differed along three dimensions, as follows.

In the first of these dimensions (cue, Fig. 1A), the instruction to move was either spatial or symbolic. As described above, spatial cues were filled circles appearing in the position of one of the target annuli. Symbolic cues were letter strings that indicated a compass direction, with N, S, E and W indicating directions up, down, right and left, respectively, and combinations of those (e.g., NW) indicating intermediate directions. These symbolic cues were presented at the center of the screen. Once presented, both spatial and symbolic cues remained visible until the end of the trial.

In the second dimension (mapping, Fig. 1A), the subjects moved either toward the appropriate target, or in a direction rotated 90° counter-clockwise.

In the third dimension (choice, Fig. 1B), the number of possible target locations could be two, four or eight. In each block of eight-choice trials (as described above), the outer circle contained eight annuli corresponding to the eight possible target locations. In each block of four-choice trials, the outer circle contained four possible targets and four small non-target markers (2-mm radius). Within a block, the same four possible targets were used, with their positions pseudo-randomly chosen (between blocks) to ensure angular distances of 45°, 135° and 225° (or −45°, −135° and −225°) with respect to the first target chosen. This placement ensured maximum angular distances between targets while minimizing the chances of placement on opposite poles. In each block of two-choice trials, the outer circle contained two possible targets and six non-target markers. The positions of the two possible targets were pseudo-randomly chosen (between blocks) to ensure an angular distance of 135°.

Subjects performed 12 blocks of trials in random order, corresponding to the 12 combinations of choice (two, four, or eight), cue (spatial or symbolic), and mapping (toward or ccw). Before each block, subjects were verbally instructed as to the type of task that would follow, and short practice blocks were provided to ensure that the subjects understood the requirements. In each practice block, subjects performed as many trials as necessary to achieve 16 correct responses, which were defined as having an angular error of less than 22.5°. Throughout the experiment, subjects were provided feedback concerning response accuracy in the form of a short tone (high pitch for correct response, low for incorrect) at the end of each trial.

For each correct response, response time was defined as the duration between cue onset and the time at which the cursor departed the central circle. A reciprocal transformation (1/response time) was used to normalize variability before statistical comparisons were made using a repeated measures ANOVA.

3. Results

Fig. 2 shows the overall pattern of response times for the 12 combinations of choice, cue and mapping. All main effects were significant, with longer response times associated with symbolic cues ($P < 0.0001$), ccw mapping ($P < 0.0001$), and higher degrees of choice ($P < 0.0001$). Furthermore, all interactions were significant (cue × choice: $P < 0.0005$; mapping × choice: $P < 0.0005$; cue × mapping: $P < 0.0001$; cue × mapping × choice: $P < 0.05$). Notably, the effect of choice on response time (Fig. 2) was greater when combined with the symbolic cue or the ccw response, and was still greater when combined with both.

To determine if the effects of cue, choice and mapping were susceptible to learning effects, we separated two subgroups from each block of trials: the first 10 correct trials (i.e., those trials with the fewest number of preceding trials that might provide learning effects), and the last 10 (i.e., those with the greatest number of preceding trials). Response times were then reexamined, including ‘learning’ as a within-subject factor. In addition to the significant main effects and interactions described above, a main effect of learning ($P < 0.0001$) was noted, with shorter response times in the final 10 trials (669 ± 56 ms, compared to 741 ± 64 ms in the first 10 trials). A significant mapping × learning interaction ($P < 0.05$) was also present, due to a decrease in the magnitude of the mapping effect in the later trials [i.e., in the first 10 trials, response times in the direct conditions (495 ± 35 ms) were 496 ms faster than in the ccw conditions (991 ± 114 ms); in the final 10 trials, response times in the direct conditions (495 ± 47 ms) were only 351 ms faster than in the ccw conditions (846 ± 96 ms)]. However, the main effect of

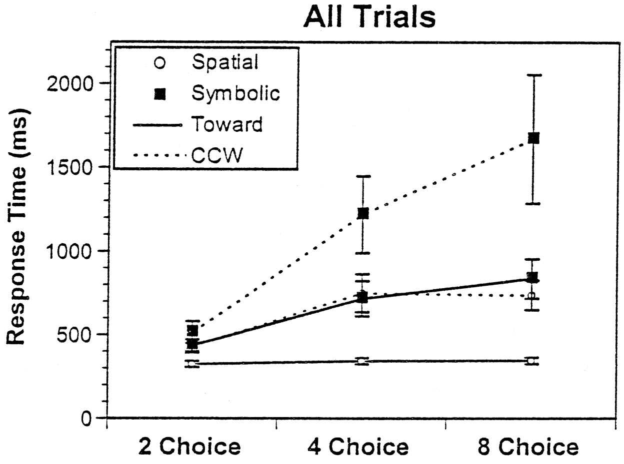

Fig. 2. Response times (mean ± S.E.M.) for each of the 12 combinations of cue (spatial/symbolic), mapping (toward/ccw), and choice (2/4/8).

mapping was still significant ($P < 0.0001$) even when the analysis was restricted to the final 10 trials from each block.

Because of the random order of target presentation, the same spatial or symbolic cues were often repeated in two or more subsequent trials. The probability of repeated cues necessarily differed with the degree of choice in a given block (50% in two-choice blocks, 25% in four-choice blocks, and 12.5% in eight-choice blocks). Because the effects of choice have been shown to be somewhat smaller for repeated trials than for non-repeated trials (see Ref. [13] for a review), we divided our data into repeated and non-repeated trials (Fig. 3) and reanalyzed the response times by including 'repetition' as a within-subject factor. As before, cue ($P < 0.0001$), mapping ($P < 0.0001$) and choice ($P < 0.0001$) were significant main effects, and cue × choice ($P < 0.0001$), mapping × choice ($P < 0.0001$), cue × mapping ($P < 0.0001$) and cue × mapping × choice ($P < 0.001$) were significant interactions. As can be seen in Fig. 3, there was also a main effect of repetition ($P < 0.0001$), with shorter response times on repeated trials. The effects of mapping (mapping × repetition: $P < 0.01$) and choice (choice × repetition: $P < 0.01$) were also smaller on repeated trials than on non-repeated trials. (The effect of cue was smaller on repeated trials, but did not reach significance; cue × repetition: $P = 0.0555$) However, main effects of cue ($P < 0.0001$), mapping ($P < 0.0001$) and choice ($P < 0.0001$) and their respective interactions (cue × choice: $P < 0.005$; mapping × choice: $P < 0.01$; cue × mapping: $P < 0.0001$; cue × mapping × choice: $P < 0.05$) were significant even when the results from repeated trials were analyzed in isolation.

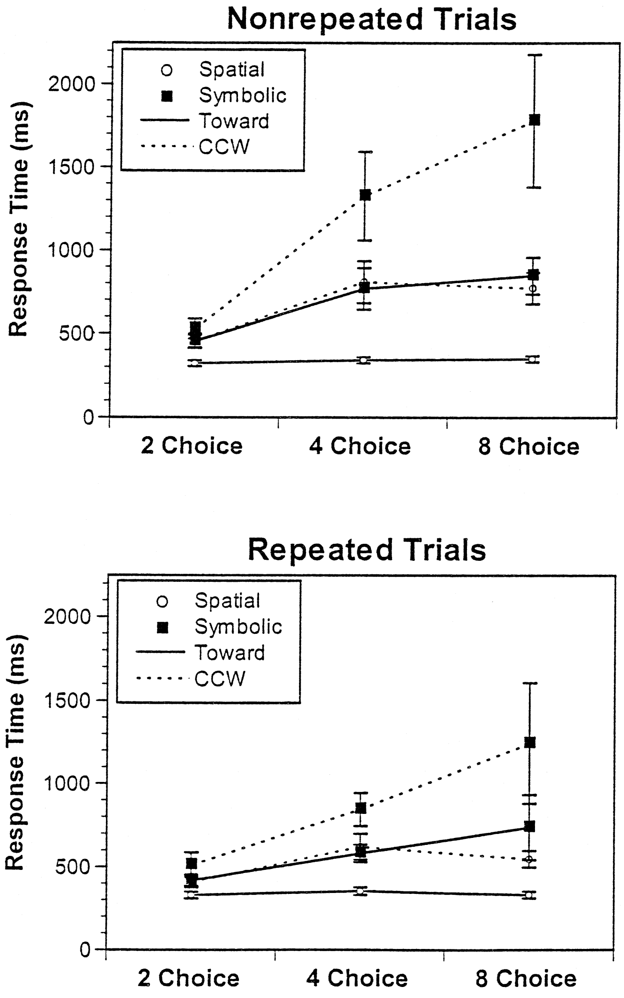

Fig. 3. Response times (mean ± S.E.M.) for repeated trials (i.e., those trials preceded by trials with an identical cue; lower plot) and non-repeated trials (upper plot).

4. Discussion

Given the results of several previous investigations, it was not surprising to find significant increases in response time associated with S–R incompatibilities [6,7,14], or with an increasing number of choices [11,12]. However, the manner in which these effects interact had not been fully described. Although it has been shown that the effect of choice is obvious only in conjunction with S–R incompatibility [1,17], it was not known whether the effect is dependent on an incongruence between stimulus and response characteristics, or on an incompatible mapping between the elements of the stimulus and response sets. Our findings clearly show that the effect of choice is dependent on either dimension of compatibility, and is greatest when the task is incompatible in both dimensions.

The effects of choice are consistent with the hypothesis that, in cases of a low degree of S–R compatibility, the appropriate response must be determined by a list-scanning search of the set of alternatives [10,14,19,21]. Furthermore, the duration of the search is increased when the S–R pair is incompatible in two dimensions. In the symbolic/ccw tasks, it is reasonable to assume that the subjects first determined the direction indicated by the symbolic cue, and only then determined the appropriate response dictated by the ccw instruction. In this way, two transformations must be conducted, increasing the response time correspondingly. According to Sternberg's additive-factor method [20], one can assess some of the properties of the sensorimotor processing stages involved in a task by examining the behavioral effects of various task parameters. The three-way interaction of cue, mapping and choice indicates that there exists at least one stage of processing that is affected by all three dimensions. It is reasonable to assume that this is associated with a corresponding modulation of neural activity in one or more anatomic regions in the brain. Imaging investigations of the underlying neural bases for these S–R compatibility and choice effects are ongoing in this laboratory [2,3].

The effects of choice size were significant for each variation in S–R compatibility, but the effects in the spatial/ccw tasks seemed somewhat inconsistent. Although there was an increase in response time between the spatial/ccw/two-choice and four-choice conditions, there was no corresponding increase between the four-choice and eight-choice conditions. Although this could be attributed to mere statistical artifact, a possible explanation can also be offered in relation to the list-rule model of S–R compatibility [10]. The ccw rotation requirement introduces a S–R incompatibility that can be resolved in one of two ways: Either the appropriate S–R relationships can be memorized and accessed via memory-list scanning (with the corresponding response time dependent on the number of choices), or they can be determined by a rule involving the mental rotation of a vector 90° ccw from the indicated direction (with the response time independent of the number of choices). Previous studies [9,16,18] of motor mental rotation have shown that response times increase linearly with the size of the required rotation angle. An interpolation of the data from Georgopoulos and Massey [9] suggests that, on average, the response times should be approximately 370 ms longer for a movement rotated 90° than for one aimed directly at the stimulus. However, depending on the number of alternative choices, it may be more efficient for the brain to use either a list scanning or mental rotation strategy. The response times of the spatial/ccw/four-choice and spatial/ccw/eight-choice conditions are consistent with a mental rotation having a duration approximately equal to that interpolated from the results of Georgopoulos and Massey [9]. In contrast, the shorter response time of the spatial/ccw/two-choice condition indicates that a list-scanning strategy is used in lieu of mental rotation. As further evidence of this, an analysis of the errors made in the spatial/ccw/two-choice condition found that 87.5% of the incorrect responses were directed to the response location appropriate for the other possible target, as would be expected if the errors were the result of an inaccurate list-scanning strategy. Only 12.5% of errors were in a direction that might be construed as the result of an inaccurate mental rotation. Thus, subjects seem capable of selecting either a list-scanning or rule-based (e.g., mental rotation) strategy depending on the number of possible S–R pairs. Although a list-scanning approach may be more efficient than a rule-based approach for a task having only a few possible S–R pairs, it may be overwhelmed by higher degrees of choice. The threshold at which a rule-based strategy becomes more efficient seems to be task-dependent, as suggested by the observation that the response times in the symbolic/ccw conditions are affected by choice size (and are therefore based on a list-scanning strategy) to at least the eight-choice condition and perhaps beyond. Indeed, some variations of S–R compatibility (e.g., random mapping between S–R pairs) preclude the use of a rule-based strategy altogether.

Although overall performance improved with practice, the effects of choice, mapping and cue (and their interactions) were significant even in the final 10 trials of each block. In fact, only the magnitude of the mapping effect changed at all during a block of trials. Although this effect was still present after 40 trials, it is not known whether the performance of additional trials would have eliminated the mapping effect completely. Examined from a different viewpoint, one can conclude that learning had a large effect in the ccw conditions (i.e., a mean reduction in response time of 145 ms between the first and last 10 trials) and no effect in the direct conditions. This finding, in conjunction with evidence (see above) that the ccw rotation can be performed with either a rule- or list-based strategy, lead us to speculate that practice in the ccw conditions provides the opportunity for subjects to reinterpret an initially rule-based ccw rotation task to one that is based on a list-scanning strategy.

Consistent with previous findings (see Ref. [13] for a review), the overall pattern of response times was very similar for repeated and non-repeated trials, with each type of trial showing main effects of cue, mapping and choice, as well as their respective interactions. From this, we can infer that the transformations necessary to convert a given sensory cue into the appropriate motor response must occur even if identical transformations occurred in the previous trial. However, the response times were significantly smaller in the repeated trials, indicating that the sensorimotor transformations of the previous trials might prime subsequent identical computations, increasing their speed and efficiency.

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References

[1] R.W. Brainard, T.S. Irby, P.M. Fitts, E.A. Alluisi, Some variables influencing the rate of gain of information, J. Exp. Psychol. 63 (1962) 105–110.

[2] P. Dassonville, X.-H. Zhu, S.M. Lewis, H.E. Foster, S.-G. Kim, K. Ugurbil, J. Ashe, Choice and stimulus–response compatibility: effect on cortical motor activation, Soc. Neurosci. Abs. 23 (1997) 1948.

[3] P. Dassonville, S.M. Lewis, S.-G. Kim, K. Ugurbil, X.-H. Zhu, J. Ashe, Cortical motor activation associated with manipulations of stimulus–response compatibility, Soc. Neurosci. Abstr. 24 (1998) in press.

[4] R. Davis, N. Moray, A. Treisman, Imitating responses and the rate of gain of information, Q. J. Exp. Psychol. 13 (1961) 78–89.

[5] M. Favilla, Reaching movements: programming time course is independent of choice number, NeuroReport 7 (1996) 2629–2634.

[6] P.M. Fitts, R.L. Deininger, S–R compatibility: correspondence among paired elements within stimulus and response codes, J. Exp. Psychol. 48 (1954) 483–492.

[7] P.M. Fitts, C.M. Seeger, S–R compatibility: spatial characteristics of stimulus and response codes, J. Exp. Psychol. 46 (1953) 199–210.

[8] A.P. Georgopoulos, J.F. Kalaska, J.T. Massey, Spatial trajectories and reaction times of aimed movements: effects of practice, uncertainty, and change in target location, J. Neurophys. 46 (1981) 725–743.

[9] A.P. Georgopoulos, J.T. Massey, Cognitive spatial-motor processes: 1. The making of movements at various angles from a stimulus direction, Exp. Brain Res. 65 (1987) 361–370.

[10] T. Hasbroucq, Y. Guiard, L. Ottomani, Principles of response determination: the list-rule model of SR compatibility, Bull. Psychonomic Soc. 28 (1990) 327–330.

[11] W.E. Hick, On the rate of gain of information, Q. J. Exp. Psychol. 4 (1952) 11–26.

[12] R.J. Hyman, Stimulus information as a determinant of reaction time, J. Exp. Psychol. 45 (1953) 188–196.

[13] S. Kornblum, Sequential effects in choice reaction time: a tutorial review, in: S. Kornblum, (Ed.), Attention and Performance IV, Academic Press, New York, 1973, pp. 259–288.

[14] S. Kornblum, T. Hasbroucq, A. Osman, Dimensional overlap: cognitive basis for stimulus–response compatibility—a model and taxonomy, Psychol. Rev. 97 (1990) 253–270.

[15] J.A. Leonard, Tactual choice reaction times, I, Q. J. Exp. Psychol. 11 (1959) 76–83.

[16] J.T. Lurito, T. Georgakopoulos, A.P. Georgopoulos, Cognitive spatial-motor processes: 7. The making of movements at an angle from a stimulus direction: studies of motor cortical activity at the single cell and population levels, Exp. Brain Res. 87 (1991) 562–580.

[17] R.E. Morrin, A. Konick, N. Troxell, S. McPherson, Information and reaction time for ‘naming’ responses, J. Exp. Psychol. 70 (1965) 309–314.

[18] G. Pellizzer, A.P. Georgopoulos, Mental rotation of the intended direction of movement, Curr. Dir. Psychol. Sci. 2 (1993) 12–17.

[19] A.F. Sanders, Some aspects of the reaction time process, Acta Psychol. 27 (1967) 115–130.

[20] S. Sternberg, The discovery of processing stages: extensions of Donders’ method, Acta Psychol. 30 (1969) 276–315.

[21] A.T. Welford, The measurement of sensory-motor performance: survey and reappraisal of twelve years’ progress, Ergonomics 3 (1960) 189–230.