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Dissociation of Bimanual Responses With the Simon Effect: On the Nonunitization of Bimanual Responses

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ABSTRACT. The authors examined whether responses of the 2 hands were completely unitized when participants (N = 36) produced bimanual responses to lateralized targets in a Simon-type paradigm. Their primary aim was to investigate whether lateralized stimuli differentially influence the response dynamics of the 2 hands. Simon effects were obtained in reaction time and force; components of the bimanual response by the hand on the same side as the lateralized stimulus were more forceful than were those of the other hand. Also, Simon effects were larger when the lateralized target appeared alone than when it was accompanied by a distractor on the other side of the display. Finally, responses of the 2 hands were correlated most strongly when stimulus displays were symmetrical. The authors conclude that bimanual responses are strongly coupled, but not perfectly so.

Key words: bimanual coupling, redundant targets, response force, Simon effect

How people coordinate multiple simultaneous movements is an important topic in motor control. The cross-talk that occurs when people try to make two independent movements at the same time has been documented in numerous studies. Those studies show, for example, that people have great difficulty making two simultaneous movements with different temporal (Klapp, 1979; Rinkenauer, Ulrich, & Wing, 2001; Yamanishi, Kawato, & Suzuki, 1981) or spatial (Franz, 1997; Franz, Zelaznik, & McCabe, 1991; Spijkers & Heuer, 1995) parameters. The results of such studies clearly indicate that the characteristics of each desired movement influence the other movement as well. With practice, distinct movement sequences can sometimes be generated without too much interfering cross-talk between them, but that seems to occur mainly through amalgamation of the different movement sequences into a coherent overall whole (e.g., Jagacinski, Marshburn, Klapp, & Jones, 1988; Klapp, Nelson, & Jagacinski, 1998). Thus, one constraint of the motor system seems to be that different simultaneous movements always tend to be at least partially coupled.

Fewer researchers have looked at a somewhat different issue: Can two simultaneous identical movements be fully unitized? Given the strong evidence that different movements are unavoidably coupled, one might expect that two simultaneous identical movements would normally be completely coupled—that is, unitized. Moreover, unitization of identical movements would seem to be adaptive on efficiency grounds because, with unitization, the motor system would have to specify only a smaller number of parameters, which it could use to control both of the two identical movements.

Although we know of no experimental designs that have enabled investigators to examine that specific question, researchers have examined movement properties of the two hands in bimanual tasks. Woodworth (1903) first documented the ease of producing simultaneous movements with the left and right hands. Following up on his analysis, Kelso, Southard, and Goodman (1979) examined bimanual Fitts-type movements to targets of a specified width and distance away from a home key. In bimanual conditions that required movements of two different difficulties, movement times of the two hands were more similar than Fitts's law would predict. In addition, the kinematics of the movements clearly demonstrated similar properties for the two hands (e.g., time of maximum velocity and acceleration). Thus, movements of the two hands were evidently strongly coupled; yet it was clear that reaction times (RTs)

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usually differed slightly for the two hands, even when the two hands were assigned identical movements. Therefore, coupling was not complete. Indeed, Marteniuk, MacKenzie, and Baba (1984) also studied Fitts-type movements with much smaller targets. They found that RT disparities between the two hands were larger and that loading the hands with differential masses further increased the disparities. The coupling of the two hands during bimanual movements is also sensitive to various other task factors, including the amount of time available for preparation of the movements (e.g., Heuer, Spijkers, Kleinsorge, van der Loo, & Steglich, 1998) and the required movement tempo (e.g., Spijkers & Heuer, 1995).

Schmidt, Zelaznik, Hawkins, Frank, and Quinn (1979) also studied bimanual movements to targets within the context of testing impulse variability models. They also found high, but not perfect, between-hands correlations for movement time and for parameters of spatial accuracy. They concluded that the majority of variability in movement time arises during selection of a motor program that is common for the two hands, but that the majority of variability in spatial endpoint accuracy results from hand-specific movement parameters.

Other researchers have also noted differences between movements in tasks in which participants are instructed to produce identical movements with the two hands. For example, when participants attempt to produce similar-amplitude movements with both hands by drawing (Franz, 1997) or moving manipulanda (Spijkers, Heuer, Kleinsorge, & van der Loo, 1997) along digitizer tablets, slight differences between the two hands tend to show up in movement amplitude, movement time, and RT differences following a common precue. Those differences may be a consequence of processes associated with executing or even programming the movements, because the processes could be quite involved even in those ostensibly simple movement tasks. For the present purposes, however, the important point about those differences is that they could reflect either neuromuscular noise or imperfect cross-hand coupling, because those two possibilities have not been separated in previous studies. Moreover, the results of recent studies have demonstrated that differences in the movement patterns of the separate hands may also occur as a result of conceptualizing the bimanual movements as two distinct tasks rather than as a single unified task (Franz, Zelaznik, Swinnen, & Walter, 2001) or as a result of attending to one hand more than the other (Franz, 2004).

We designed the present experiment to investigate the degree of unitization of identical bimanual movements in a task intended to maximize the opportunity for full unitization and yet also to maximize the chances of detecting evidence that unitization is less than perfect, if indeed it is. Specifically, we asked participants to make bimanual key press responses in a go/no-go RT task. In each trial, they were to monitor for a visual target stimulus, responding by pressing keys with the index fingers of both hands if one or more targets appeared but doing nothing if one or more distractors appeared. The response requirements seem optimal for unitizing the two components of the bimanual response because (a) the desired characteristics of the responses of the two hands were identical; (b) the two component key presses of the bimanual response were to be emitted at exactly the same time (i.e., following detection of the target stimulus); (c) the two key presses were required only in combination—never in isolation from one another—so, they could in principle be fully prepared as a complete unit in advance of the trial; and (d) there was no reason to suspect that participants would conceptualize that type of task as having distinct components for the two hands.

We used a version of the Simon effect (Simon, 1967, 1969; Simon & Rudell, 1967; Simon & Small, 1969) as our primary experimental manipulation to see whether the two components of the bimanual key press response were fully unitized. The Simon effect is a well-known and highly replicable phenomenon in choice-RT tasks with unimanual responses. Specifically, the effect is that people respond faster to stimuli appearing on the same side as the responding hand than to stimuli appearing on the opposite side, even though stimulus side is irrelevant to the response. In recent examinations of the Simon effect in which psychophysiological measures were used, activation from a lateralized stimulus was found to feed directly into the response channel associated with the hand on the same side, producing motor activation of the ipsilateral hand, which speeded its response (e.g., Eimer, 1995; Valle-Inclán, 1996; Wascher, Verleger, & Wauschkuhn, 1996; see also Kornblum, Hasbroucq, & Osman, 1990). In essence, we used the Simon effect to try to "split the atom" of the unitary bimanual response.

Specifically, the empirical question of primary concern to us was whether an analog of the Simon effect would occur within the two components of a bimanual response. If the two-component key presses are not fully unitized, then a Simon-like effect may be found. In that case, the hand ipsilateral to the stimulus will produce faster and presumably more forceful responses than will the contralateral hand, despite the fact that the two key presses are part of the same overall (bimanual) response. A finding of such an effect would suggest that the two components of the bimanual key press response are not completely unitized.

In contrast, if the two components of the bimanual response are fully unitized, then no such Simon effect should occur. In that case, the two hands would be treated as a single effector, and the parameters of the two combined key press responses could be fully specified in advance. If those responses are completely coupled, then the location of the stimulus should not create a differential between hands, because both hands would receive the same activation by virtue of their complete coupling.

Our experiment included nine different stimulus conditions constructed as a factorial combination of three possible stimuli on the left side of the display and three possible stimuli on the right (see Table 1). On each trial, each side could contain no stimulus (_), a distractor stimulus (o), or a target stimulus (X). As is characteristic in Simon paradigms, we used both target and distractor stimuli so that participants would discriminate among stimuli. In addition, we included no-stimulus trials to contribute to ongoing investigations (e.g., O'Leary & Barber, 1993; Valle-Inclán, 1996) of the extent to which the Simon effect depends on the presence or absence of a target and the extent to which it depends on the presence of some stimulus energy or no stimulus energy. Moreover, we ensured that the stimulus presented on one side was independent of the stimulus presented on the other side to avoid interstimulus contingencies (Mordkoff & Yantis, 1991).

We included the final experimental manipulation in our study to affect the participants' levels of response preparation at the start of a trial. Specifically, we included a precue in each trial to indicate to the participant whether the go response was likely or unlikely on that trial. Such precues have been found to have substantial effects on the speed and forcefulness of responses (Franz & Miller, 2002; Mattes, Ulrich, & Miller, 1997, 2002), so there is good reason to believe that people prepare the go response more fully when it is likely to be required than they do when it is unlikely to be required. Of interest in the present study was whether the extent of response preparation influences the degree of coupling of the two components of the bimanual response. One might expect, for example, that higher levels of preparation would produce greater coupling.

In addition to studying the Simon effect as an index of bimanual coupling, we reasoned that we could also assess the degree of coupling by looking at the correlation, across trials, of the RTs and forces measured for the two hands separately. If the hands are well coupled, for example, then their RTs should be almost perfectly correlated; if not, then the correlation should be weaker. The same argument can be made about force. Thus, we sought to use between-hands correlations to gain further information about the degree of coupling between the two components of the bimanual response. In particular, if those correlations varied across stimulus conditions or across levels of preparation, then that variation would provide further evidence that unitization was not complete in all conditions.

In summary, we designed the present study to assess Simon effects on bimanual responses, incorporating bilateral stimulus manipulations and response probability into the Simon paradigm. We measured both RT and force output on bimanual key press responses with the primary aim of examining whether bimanual responses are unitized.

Method

Participants

Undergraduates (9 men and 27 women) from the University of Otago Psychology Department participant pool took part in the experiment. Their age range was 17–35 years (M = 21.7 years). The average handedness score on the Oldfield inventory (Oldfield, 1971) was .66, on a possible range from –1.00 (*strongly left-handed*) to +1.00 (*strongly right-handed*). Participants gave informed consent for their inclusion in the study, which was approved in accordance with procedures of the Human Ethics Committee of the University of Otago.

Apparatus

Participants were tested individually in a small, dimly lit testing room. A microcomputer controlled stimulus presentation and recorded response force. We placed an adjustable chinrest approximately 57 cm in front of the computer monitor, and we used the chinrest to minimize head movements. A set of written instructions was displayed in white with black background on the computer screen; the target letters were highlighted in color for emphasis. One set of instructions appeared before each block of trials and during each rest period, and the instructions remained constant across all blocks per participant. We used a foot-operated pedal placed under the table to initiate the first trial for each block. The stimuli were the letters X and o, presented as white figures on the dark background of the computer screen. The letters were 2.5° in height, and they were presented 5.6° to the left or right of a fixation square that was 0.3° on a side. Participants were seated on a standard desk chair in front of the computer screen; they placed their chin in the chinrest, which was adjusted to a comfortable height. They were instructed to respond with a brief flexion of the left and right index fingers on all trials in which the target stimulus X appeared on either or both sides of the screen, and to do nothing (no-go trials) if no X was presented. We measured responses by using force-sensitive keys. A leaf spring (140 × 20 × 2 mm) was supported in a clamp on one end of each response key, and participants pressed the side that was freely appended. A force of 15 N bent the free end of the leaf spring approximately 2 mm. Strain gauges (Type 6/120 LY 41; Hottinger Baldwin Messtechnik, Darmstadt, Germany) were attached near the fixed end of the leaf spring, and the applied force was reflected in an analogue signal with a resolution of approximately 2.8 mN. The digitized force signal was recorded at 250 Hz starting 200 ms before stimulus onset and continuing for 2.2 s. RT was therefore measured to the nearest 4 ms; that resolution should be quite adequate for uncovering experimental effects of 10 ms or more (Ulrich & Giray, 1989). Participants used both index fingers to press the force keys; each arm and hand was supported by individual armrests located on the two sides of the computer. Their arms rested comfortably, with slightly bent elbows, and their body was positioned directly in front of the computer monitor located 57 cm away. Participants were instructed to sit so that their body posture was symmetrical, and they were reminded if they began to slump in any way. They were also given a rest if that occurred.

Procedure

Each participant was tested in a single experimental session that lasted approximately 1 hr. A session consisted of two equivalent blocks of 197 trials each, with rest periods interspersed approximately every 60 trials. The number of trials per block in each experimental condition is shown in Table 1. We selected those numbers of trials to satisfy the following three constraints simultaneously: (a) Cues indicating high versus low response probability should occur approximately equally frequently; (b) following a high-probability cue, the probabilities of target, distractor, and no stimulus were to be .60, .20, and .20, respectively, at both the left and right stimulus locations, with the two locations being independent of one another; and (c) following a low-probability cue, the three probabilities were to be .10, .45, and .45, respectively.

Each trial began with the appearance of the small fixation square and a simultaneous change of the computer screen's background color from black to either blue or green. The color change indicated that the go probability was either high or low for the current trial; the assignment of background color to probability was counterbalanced across participants. We added the X or o stimuli, or both, to the screen 1.1 s after the onset of the fixation point and cuing color. The stimuli remained on the screen for 100 ms; we then removed them to leave just the cuing color and fixation point. After the participant responded by generating at least 100 cN of force on either force key or after 2 s had elapsed, whichever came first, the screen's background color changed back to black and feedback was given. If an X had been presented and both force keys had been pressed or if no X had been presented and neither key was pressed, then the word *Correct* was displayed for 600 ms. In the other cases, the computer produced its standard tone and the word *Error* was displayed for 1.2 s.

Data Analysis

To compute the percentage correct, we tallied trials that were in error because there was no response when a response was required, only one hand pressed the key for a bimanual response, or a response was produced for a no-go trial. For each stimulus condition that included one or more targets, RT was computed for each hand's response as the time at which the force first exceeded the criterion level of 100 cN. Mean RT was then computed for high- and low-probability trials with each stimulus type separately. Peak force (PF) and force impulse size (IS) were computed as measures of force for all types of target-present trials. PF was computed as the maximum force produced by the hand on a given trial. IS was computed as the total integrated force for that hand in excess of the criterion level of 100 cN. Although PF and IS tend to be highly correlated (e.g., Giray & Ulrich, 1993), by computing both measures one can often reveal patterns in the data that one measure alone would not reveal (see Franz & Miller, 2002).

It was more difficult to analyze force—and impossible to analyze RT—for no-go trials (i.e., trials without a target stimulus) because those trials did not result in regularly shaped force profiles. Following Franz and Miller (2002), we computed the mean force output of each finger in each of ten 100-ms windows, beginning at the end of the 200-ms prestimulus baseline-recording period of each trial. The first of those windows thus started at the onset of the left, right, or bilateral distractor stimulus in the stimulus conditions _o, o_, and oo of Table 1 (o = letter *o* stimulus, _ = no stimulus), or from the time when the stimulus would have been presented in the no-stimulus condition (__). Average force levels were miniscule, generally ranging from 0.5 to 1.2 cN, and they were independent of the probability of the go response. In the time intervals from 100–500 ms poststimulus, there were tendencies toward slightly greater force when two distractors were presented than when only one was, but those reached significance in only a few comparisons. There was no evidence of the Simon effect in the no-go trials with a single distractor—that is, force output was not greater in the hand on the same side as the distractor than in the hand on the opposite side.

The results section is divided into four primary subsections. Following a brief description of the data on percentage correct, we discuss the Simon effects with respect to bimanual responses. Then we report results on the effects of probability, the effects of redundant stimuli, and the correlation of response properties across hands.

TABLE 1. Stimulus Display, Required Response, and the Number of Trials of Each Type Per Block for High and Low Probability Cues (#Hi and #Lo)

	Stimulus								
	__	_o	_X	o_	oo	oX	X_	Xo	XX
Response	no	no	go	no	no	go	go	go	go
#Hi	4	4	12	4	4	12	12	12	36
#Lo	20	20	4	20	20	4	4	4	1

Note. X and o = target and distractor, respectively; and _ stands for no stimulus.

Results

The percentages of correct responses as a function of display type and response probability are shown in Table 2. It was not surprising that responses were quite accurate overall in this simple task. We conducted a two-factor repeated-measures analysis of variance (ANOVA) with a nine-level factor of stimulus display type, corresponding to the nine different stimulus displays listed in Table 1, and a two-level factor of cued response probability. The ANOVA revealed a significant effect of display type, $F(8, 280) = 5.80$, $p < .001$, and a significant interaction of display type and response probability, $F(8, 280) = 2.86$, $p < .02$. Inspection of the averages revealed that the interaction reflected a greater tendency to make false alarm errors on no-go trials when go probability was high than when it was low.

Simon Effects

We evaluated Simon effects by using all of the conditions with a single target in the display (i.e., stimulus conditions _X, oX, X_, and Xo in Table 1). We computed separate repeated measures ANOVAs for each dependent variable (RT, PF, IS) by using the variables cued response probability (high, low), target side (left target, right target), distractor (present, absent), and response hand (left, right). A significant interaction between response hand and target side would indicate the presence of a Simon effect, on average, across experimental conditions, and three-way interactions of target side, response hand, and either response probability or distractor presence would indicate that the size of the Simon effect depended on the level of the third variable.

The grand mean RT was approximately 400 ms. In the factorial analysis of RT, the result of primary importance was the highly significant Response Hand × Target Stimulus Side interaction, $F(1, 35) = 27.58$, $p < .001$. Overall, mean RT was 382 ms for the hand ipsilateral to the target as compared with 386 ms for the contralateral hand. Although the interaction was numerically small, it was remarkably consistent across participants, as indicated by the highly significant *F* value. In addition, as can be seen in Figure 1, it was also fairly consistent across experimental conditions. Thus, that interaction revealed a novel Simon effect with bimanual responses. It also indicated that the responses of the two hands were not completely unitary, given that the Simon effect differentially influenced the RT of the hands ipsilateral and contralateral to the target stimulus. Most interesting, the advantage of ipsilateral over contralateral RTs tended to be much stronger when the stimulus was on the right side of the display than when it was on the left (cf. Figure 1). The asymmetry could have arisen as a result of faster responding with the dominant right hand than with the nondominant left hand. When the stimulus was on the right side of the display, the right-hand advantage added to the ipsilateral advantage. In contrast, when the stimulus was on the left side of the display, the right-hand advantage subtracted from the ipsilateral advantage. That asymmetry simply emphasized that the overall interaction was the most appropriate test of the ipsilateral advantage because the main effects of both stimulus side and response hand were taken into account in that interaction.

The force measures also revealed highly significant Simon effects: Greater force was produced by the hand ipsilateral to the target than by the contralateral hand. For both force measures, PF and IS, the Response Side × Target Stimulus Side interaction was highly significant, Fs$(1, 35) = 28.35$, and 40.39, respectively, both ps $< .001$. That effect, shown in Figure 1, complemented that of RT.

One can assess the dependence of the Simon effect on response probability and on distractor presence via the three-way interactions of those factors with response hand and target side. Distractor presence had a strong influence on the Simon effect, producing significant three-way interactions for RT, $F(1, 35) = 7.17$, $p < .02$; for PF, $F(1, 35) = 16.57$, $p < .001$; and for IS, $F(1, 35) = 12.31$, $p < .002$. As can be seen in Figure 1, the Simon effect on each dependent variable was smaller when a distractor was present than it was when the target stimulus appeared alone. Thus, the Simon effect on bimanual responses is at least partly sensitive to the lateralization of the stimulus energy in the display. Further analyses were conducted that included only

TABLE 2. Percentage of Correct Responses as a Function of Display Type and Response Probability

	Stimulus								
	__	_o	_X	o_	oo	oX	X_	Xo	XX
Response	no	no	go	no	no	go	go	go	go
	Percentage correct responses								
Hi	100.0	96.9	96.9	99.1	93.3	97.9	97.3	99.2	98.7
Lo	99.9	99.2	97.0	98.9	97.4	98.8	98.0	97.7	98.1
Avg	100.0	98.0	96.9	99.0	95.3	98.4	97.7	98.4	98.4

Note. Hi and Lo = high and low response probability, respectively. Avg = average.

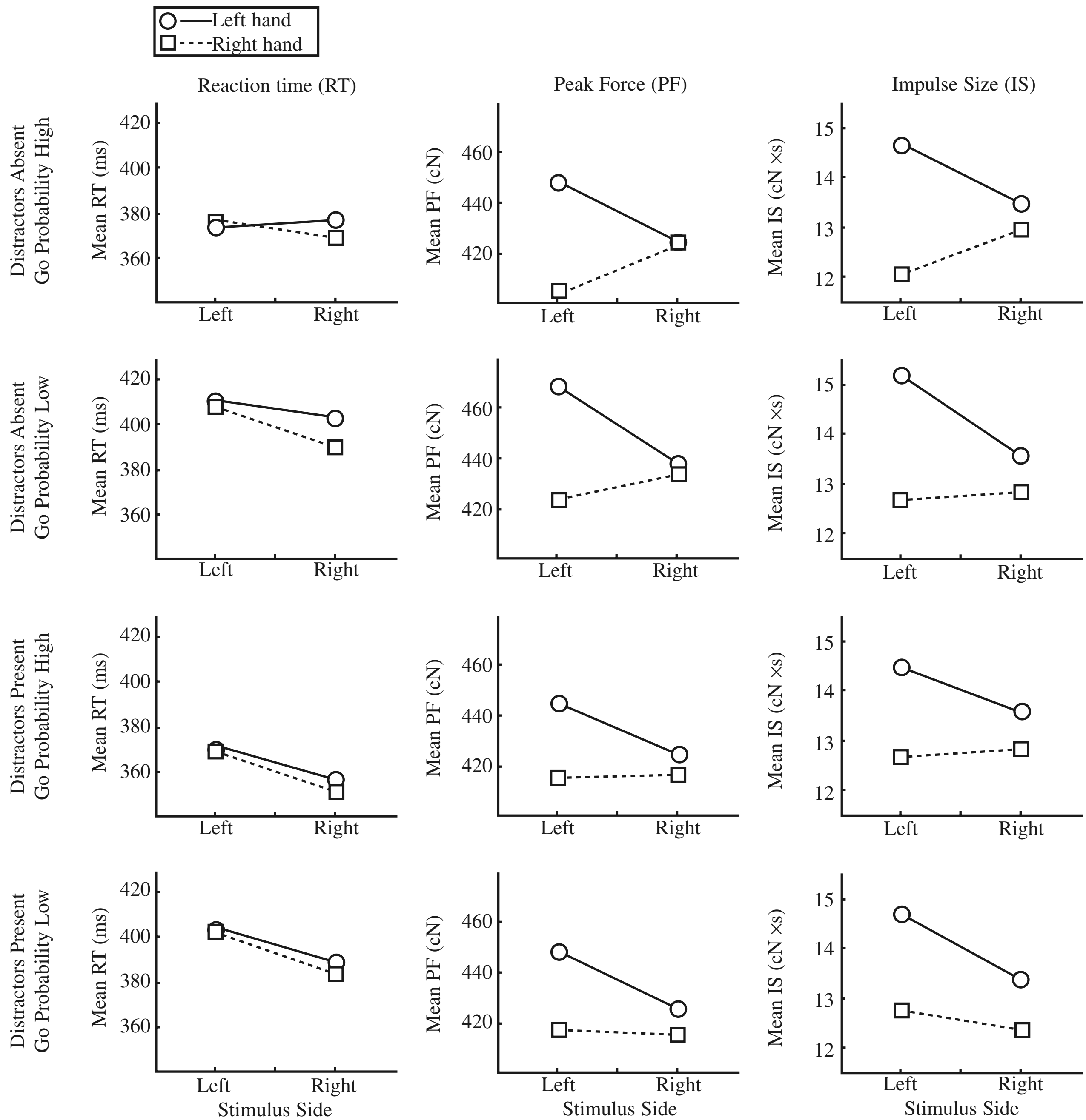

FIGURE 1. Response Hand × Target Stimulus Side interaction as a function of cued go probability and presence or absence of distractor for reaction time (RT), peak force (PF), and impulse size (IS).

the data from the distractor-present conditions; however, those analyses also produced significant interactions of response hand and target side for RT, $F(1, 35) = 60.04$, $p < .001$; PF, $F(1, 35) = 12.75$, $p < .01$; and IS, $F(1, 35) = 16.21$, $p < .001$. Thus, a Simon effect, rather than requiring a unilateral target in complete isolation, occurs even in the presence of another stimulus that is not a target. It appears, then, that both pure stimulus energy and target status contribute to the overall Simon effect.

Finally, the interactions of response hand, stimulus side, and go probability were not significant in the analysis of either RT, PF, or IS, $F(1, 35) < 1.00$, $p > .50$, in each case. As shown in Figure 1, the extent of the Simon effect was quite comparable in conditions with high versus low probability of the go response. As discussed in the introductory comments, the fact that the Simon effect is reasonably independent of go probability suggests that it is not produced by inadequate advance preparation of responses.

Instead, it appears that the Simon effect is a more or less direct consequence of the processing that occurs after stimulus onset. That finding therefore supports the hypothesis that responses can never be perfectly unitized, although it is logically impossible to prove that hypothesis.

Because there is some evidence that the Simon effect dissipates over time (e.g., Hommel, 1994), we also checked to see whether the Simon effects in our data differed for fast and slow trials. To that end, we divided each participant's data in each condition into fast versus slow trials via a median split on RT; that division yielded sets of trials differing by 112 ms in average RT. Then we conducted ANOVAs with the additional variable of fast versus slow trials. The Simon effect was slightly but significantly ($p < .05$) larger for the slow trials than for the fast ones in both RT and PF, so there is no evidence that the Simon effect dissipated rapidly within the trial in this paradigm.

In addition to the Simon effects just discussed, several other significant effects were obtained in the overall four-factor ANOVAs used to assess the Simon effects with unilateral targets. In the analysis of RT, responses were 31 ms faster, on average, when cued response probability was high than they were when it was low, $F(1, 35) = 34.51$, $p < .001$. Responses were also 11 ms faster, on average, when the target appeared on the right side of the display than when it appeared on the left, $F(1, 35) = 13.38$, $p < .01$. In addition, right-hand responses were 4 ms faster than left-hand responses, on average, $F(1, 35) = 5.32$, $p < .05$, and responses were 10 ms faster when a distractor was present than when it was absent, $F(1, 35) = 7.15$, $p < .025$. The latter effect presumably reflected an overall facilitation of RT with higher stimulus intensity (Cattell, 1986; Kohfeld, 1971; Miller, Ulrich, & Rinkenauer, 1999; Ulrich & Stapf, 1984; Van der Molen & Keuss, 1979).

There was also a significant interaction of response hand and distractor presence, $F(1, 35) = 4.20$, $p < .05$, with a slightly greater advantage for right-hand responses than for left-hand responses when distractors were absent (5 ms) than when they were present (3 ms). Moreover, that two-way interaction was qualified by go probability, with a greater two-way interaction when the go probability was low than when it was high, leading to a significant three-way interaction of those factors, $F(1, 35) = 5.26$, $p < .05$.

Only a few additional significant effects were found in the ANOVAs of the force measures. Significantly more force was produced when the stimulus was presented on the left side than when the stimulus was presented the right side, as measured by IS, $F(1, 35) = 4.69$, $p < .05$, and there was a tendency in the same direction for PF, $F(1, 35) = 2.90$, $p < .10$. Consistent with previous reports (e.g., Franz & Miller, 2002; Mattes et al., 1997, 2002), PF was larger when go probability was low than it was when it was high, $F(1, 35) = 4.24$, $p < .05$, although a weak effect in the same direction on IS did not approach significance, $F(1, 35) < 1$, $p > .5$. Virtually all of the effect of probability on PF arose when distractors were absent rather than present, leading to a significant interaction of response probability and distractor presence, $F(1, 35) = 4.33$, $p < .05$. Again, however, the analogous effect on IS failed to approach significance, $F(1, 35) < 1$, $p > .5$.

Further Analyses of Probability Effects

We were surprised to find that the effects of probability on response force were not robust for bimanual responses, because results of previous research have shown fairly strong probability effects on force properties of unimanual responses (see introductory comments). That result led us to question whether the effects on force properties may be prevalent for the hand that hits the response key first (leading hand) with bimanual responses. Notably, in bimanual RT tasks, although instructions are to hit the two keys simultaneously, in other studies there almost always has been a small RT difference between hands on average across trials (Shen & Franz, 2003; Ulrich & Stapf, 1984). In the present study, the right hand led on approximately 53% of trials, the left hand led on approximately 36%, and RT was identical for the two hands on approximately 11% of trials; however, the tendency for the right hand to lead on a higher percentage than the left did was only marginally significant ($p = .11$). We reanalyzed the data with respect to the hand that hit the key first to determine whether the effects of probability would be more pronounced on the initial key press of each trial. Despite our own doubts concerning that possibility, the analysis revealed that for the leading hand, PF was significantly smaller on high- than on low-probability trials (449 vs. 465 cN), $p < .01$. In contrast, for the lagging hand, the small difference between high- and low-probability trials (394 vs. –397 cN) was not reliable, $p > .05$. That novel effect is intriguing because it suggests that the effects of response readiness on force properties of the leading hand in bimanual responses are more similar to what would be expected for unimanual responses, as though the leading hand absorbs the primary effects of response readiness and the lagging hand gets only small residual differences associated with response readiness. That effect is potentially important to our basic understanding of bimanual responses.

Correlation Analyses

As outlined in the introduction, between-hands correlations can provide further information about the degree of coupling of the two components of the bimanual response. To assess those correlations, we first computed separately for each participant the correlations across trials of the RT values of the two hands, the PF values, and the IS values. For each dependent measure (RT, PF, IS), correlations were computed separately for each of five stimulus types that required go responses (i.e., stimulus conditions _X, oX, X_, Xo, and XX in Table 1). Only trials with a high-probability cue were included because there were too few go trials following the low-probability cue for reliable estimation of correlations. For example, we obtained one correlation value for each participant by correlating the left- and right-hand RTs across all of the trials with a high-probability cue and a single target stimulus on the left side of the display.

The correlation analyses indicated that the hands were very well coupled, with an average correlation of approximately .97 for the RTs of the two hands and approximately .75 for the PFs and ISs. The almost perfect correlation for RTs is comparable with that reported by Ulrich and Stapf (1984). The somewhat lower correlation for the force measures is still quite high, and it is in fact near the top of the range of correlations—approximately .60 to .80—reported by Rinkenauer et al. (2001). Given that many of the correlations approached the ceiling of 1.00, we transformed them for analysis by using Fisher's r-to-z transformation (Marascuilo, 1971). Then, we computed repeated-measures ANOVAs for each type of transformed correlation (i.e., RT, PF, and IS), comparing the correlations across three stimulus conditions: target alone, target plus distractor, and redundant targets. The results were clearcut: Correlations were substantially lower when the display contained a single target alone than when it contained a target plus distractor or two targets. That pattern led to a highly significant main effect of stimulus type in the analyses of RT and IS correlations, both ps < .025, and to a marginally significant effect in the same direction in the analysis of PF correlations, $p < .11$. For all three types of correlations, post hoc tests indicated significant differences between the target-alone correlations and the correlations obtained with one or both of the other two stimulus conditions, whereas those other two conditions did not differ from one another. Thus, the conclusion from the correlation analyses is that the degree of coupling between the two hands depends on the stimulus conditions, being especially strong when stimulus energy is distributed symmetrically across the two sides of the display. That conclusion converges with that emerging from the analyses of the Simon effect in showing that the two components of the bimanual response are not completely coupled.

Effects of Redundant Targets

We assessed the effects of presenting redundant targets by comparing the results for the two-target conditions (Stimulus Conditions XX of Table 1) against those of the two single-target conditions. We made one such comparison by using the single-target plus distractor conditions (Stimulus Conditions oX and Xo), and a second comparison by using the single-target-alone conditions (Stimulus Conditions _X and X_). Both comparisons indicated that responses were significantly faster with redundant targets than with single targets ($p < .01$); in fact, a further comparison indicated that responses were faster when distractors were present than when they were not ($p < .01$). Analyses of the RT distributions in which we used the race model inequality developed by Miller (1982) revealed highly significant ($p < .01$) violations of that inequality—and thus support for coactivation models—when distractors were absent but not when they were present. None of the response force measures varied significantly between single- and redundant-target trials in either comparison, contrary to previous reports of more forceful responses with bimodal redundant stimuli (e.g., Giray & Ulrich, 1993; Plat, Praamstra, & Horstink, 2000) and reports that response force increases with the number of stimuli in a display (Mordkoff, Miller, & Roch, 1996). It is not yet clear why force did not vary with the number of stimuli or targets in this experiment.

Discussion

We set out to examine in this study whether bimanual responses are completely unitized under circumstances encouraging identical and fully coupled movements of the two hands. That question is novel in the context of the existing literature on bimanual movements; in those reports, the primary emphases have been placed on (a) the principles and properties that result in inadvertent or inappropriate interactions between the hands with respect to the instructed requirements of the tasks (Klapp, 1979; Rinkenauer et al., 2001) and (b) limitations of bimanual coupling in tasks requiring complex bimanual movements (e.g., Kelso et al., 1979; Schmidt et al., 1979). We attempted to control for those factors that are known to result in bimanual interactions, such as differing temporal, spatial, and force properties, by holding them constant for responses of the two hands. We also described the task to participants as requiring "a bimanual response" to encourage them—as much as possible—to conceptualize the responses of the two hands as unified. We then considered whether, under those conditions, the smallest unit of programming is the bimanual unit ("bimanual atom") or whether certain circumstances would reveal that the bimanual response still has somewhat separate component parts corresponding to the responses of the two hands, as would be inferred from independent influences on each.

Our main tool in the attempt to split the bimanual atom was the well-known Simon effect, in which the spatial or directional properties of a stimulus, or both, influence the properties of the response (Simon, 1967, 1969; Simon & Rudell, 1967; Simon & Small, 1969). As had previously been demonstrated repeatedly in unimanual tasks, right-hand responses are faster to a stimulus that appears in the rightmost of two possible locations than to one that occurs in the leftmost location (opposite the impending response), and vice versa for left-hand responses. Psychophysiological measures indicate that that effect arises at least partly because a lateralized stimulus directly activates the response hand on the same side (e.g., Eimer, 1995; Valle-Inclán, 1996; Wascher et al., 1996). In the present study, we sought to contribute to that literature by examining whether differential response properties would also be demonstrated in a task using bimanual rather than unimanual responses, which would be taken as evidence of a preserved Simon effect in bimanual responses. That evidence would also indicate that the bimanual response is not completely unitized, because preservation of the Simon effect within the bimanual setting would reveal that responses of the two hands could be influenced separately.

Our findings were clear and straightforward. Simon effects for RT still occurred for bimanual responses despite our use of conditions designed to optimize coupling. In addition, a novel extension of that finding is that Simon effects also occurred in the force properties of the responses.

The present finding of a Simon effect within bimanual responses is somewhat at odds with the results of Kaluzny, Palmeri, and Weisendanger (1994). Kaluzny et al. used mild electric shocks to one hand or the other as stimuli, and in one condition they required bimanual responses to any stimulus (i.e., simple RT). They were primarily interested in comparing RTs of the shocked hand with those of the other hand as a measure of interhemispheric transmission time. In essence, however, that is an ipsilateral versus contralateral difference analogous to our examination of the Simon effect. Surprisingly, Kaluzny et al. found no such effect, and they suggested that the two components of the bimanual response may have been fully unitized in their study. Many considerations weaken that secondary conclusion from their results, however. First, the ipsilateral versus contralateral difference is extremely small in simple RT tasks, weakening any inference from its absence, and, in fact, small differences are often found with bilateral responses (see Berlucchi, Aglioti, & Tassinari, 1994, for a review). Second, Kaluzny et al. also failed to find an ipsilateral versus contralateral difference in the unimanual conditions of their study. Given that such differences are normally found in unimanual conditions, that suggests that some aspect of their procedure may have obscured the small effect. For example, one rather atypical characteristic of their study was that stimulus side was fixed throughout a block of trials, which would certainly reduce the salience of that stimulus variation and possibly allow advance preparation that would negate the effects of stimulus side. Third, only 6 participants were tested, with about 200 bimanual responses each; so it is not clear that the study had enough statistical power to detect the effect in the bimanual condition.

Given that we found similar Simon effects for trials with high- and low-probability cues, it appears that those effects are not a result of incomplete response preparation. The effects obtained with that probability manipulation also enabled us to extend previous findings on unimanual tasks to include some properties of bimanual tasks. Consistent with findings from unimanual tasks (Franz & Miller, 2002; Mattes et al., 1997, 2002), RT was faster for bimanual responses that were preceded by high-probability cues than for those preceded by low-probability cues. Most interesting, however, previous findings of more forceful responses following low-probability cues than following high-probability cues were only marginally replicated with bimanual responses. Specifically, such effects on force output were obtained primarily with the responses of the first hand to respond within the bimanual response pair, and not with the pair as a whole. It would appear that the leading response hand absorbs the primary effects of response readiness on force properties, despite the fact that both hands reflect the effects of probability on RT. That result provides yet another data point for the argument that the effects of response probability (readiness) on force and RT appear to be somewhat dissociable (Franz & Miller).

A second line of evidence used to assess the degree of unitization of the two components of the bimanual responses involved looking at the correlations of the RTs as well as the force outputs across the two hands. As would be expected with bimanual responses, those correlations were quite high in all conditions. Crucially, however, the correlations were higher with bilateral stimulus displays (i.e., target plus distractor or two targets) than with unilateral stimulus displays (i.e., target alone). That pattern also supports the conclusion that the two components of the bimanual response are not fully coupled, because, if they were fully coupled, then the correlation between them should not be sensitive to the contents of the stimulus display. Like the Simon effect, then, this correlation-based evidence suggests that lateralized stimulus information in the display preferentially influences the ipsilateral hand, and therefore maximal coupling requires bilateral displays.

The conditions included in this experiment enabled us to demonstrate the basic Simon effect by using bimanual responses and to provide further insight into the nature of Simon interference. Specifically, we used not only single-stimulus trials that consisted of a target presented on the left or right side, but also trials that consisted of a target and a distractor presented on opposite sides. The results showed that Simon effects are reduced when a distractor is present on the side opposite the target stimulus, compared with the condition with a target alone. That finding extends and cements the preliminary conclusions of O'Leary and Barber (1993) and Valle-Inclán (1996) in that Simon interference results not only from the presence of a target but also from the summation of stimulus energy, whether or not from a target. That interpretation is strengthened further by our finding that responses were approximately 10 ms faster when a distractor was present than when it was absent, suggesting an overall facilitation of RT with higher stimulus intensity (Cattell, 1886; Kohfeld, 1971; Miller et al., 1999; Van der Molen & Keuss, 1979).

The results of this experiment also bear on two current theoretical explanations of Simon effects in tasks requiring choices between left and right responses. First, such effects are sometimes attributed at least partly to congruence between the location of the stimulus and its meaning as an indicator of the left versus right response (e.g., Hasbroucq & Guiard, 1991). Such congruence effects could not contribute to the present Simon effects, however, because the stimuli were associated with go and no-go responses rather than with left and right responses. Thus, the present results suggest that such congruence is unlikely to be entirely responsible for Simon effects. Second, Simon effects in left- versus right-hand choice tasks are sometimes thought to arise during the process of inhibiting the unselected hand (e.g., Buckolz, O'Donnell, & McAuliffe, 1996). Again, such inhibition could not contribute to the Simon effects observed here, because neither hand needs to be inhibited when making a bimanual response.

Our findings clearly illustrate that the stimulus energy from a visual display influences the coupling of bimanual responses. Specifically, bimanual responses were very strongly coupled in all of the cases we studied, but they were measurably better coupled when the stimulus information was symmetrical with respect to the participant's viewpoint than when it was not. That result is of course quite consistent with the conclusions of previous studies of Simon effects with unimanual responses. The results of those studies suggest that a lateralized stimulus selectively activates a response tendency of the hand ipsilateral to that stimulus (e.g., Kornblum et al., 1990), and such unilateral activation would tend to decouple any bimanual responses that were intended to be identical.

In summary, although we realize that it is logically impossible to prove the hypothesis that bimanual responses are never fully coupled, the present results provide strong evidence that full coupling is at best quite rare and would likely be achieved only under very special circumstances that would appear to require symmetrical stimulus displays. Although some degree of coupling is clearly the rule even when responses are intended to be different, neural fission of the bimanual atom can be accomplished by the directional properties of stimulus energy even when responses are intended to be identical.

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