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RESEARCH ARTICLES

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Experimental disentangling of spatial-compatibility and interhemispheric-relay effects in simple reaction time (Poffenberger paradigm)

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Abstract Spatial-compatibility effects can be obtained in simple reaction time (SRT) provided that spatially distinct responses are frequently required. Since this effect is limited to trials with relatively long reaction times (RTs), Hommel (1996b) proposed that if the response does not occur shortly after stimulus detection, then the spatial code of the stimulus can interfere with that of the response. A series of experiments is reported showing that (a) spatial compatibility in SRT to lateralized stimuli is not an alternative, but rather a complementary, explanation to interhemispheric transfer time (contrary to what Hommel surmised), and (b) the spatial compatibility component is essentially limited to the first trial after shifting response preparation from one-half of the visual fields to the other, suggesting a mechanism akin to an orienting response.

Keywords Poffenberger · Interhemispheric relay · Simple reaction time · Spatial compatibility

Introduction

Poffenberger (1912) was the first to propose that the crossed-uncrossed difference (CUD) is an index of interhemispheric transfer time (IHTT). In short, because vision is represented in the hemisphere contralateral to a lateralized stimulus, and because motricity is represented in the hemisphere contralateral to a responding hand, a unimanual response to a small, brief, visual stimulus presented to the opposed field (crossed condition) should take longer than a response to a stimulus in the ipsilateral field (uncrossed condition) because of the necessity of an interhemispheric transfer in the former but not in the latter condition. Poffenberger believed that the CUD was nothing other than IHTT. Several hundred reports have since been published pertaining to this particular inference. There is no doubt that IHT proper contributes to the CUD, at least in pathological conditions. While normal subjects typically present a CUD of 2–4 ms (see Braun 1992 for a review), callosotomized and callosally agenesic patients present much longer CUDs (Corballis 1998; Di Stefano and Salvadori 1998; Marzi et al. 1999).

Spatial compatibility in response-choice RT

The CUD can, however, index other phenomena besides IHTT proper. CUDs of the order of 50 ms, far beyond any plausible interhemispheric relay time, can be obtained, either in choice RT or in go/no-go tasks. That these CUDs are not primarily IHTT is demonstrated by an inversion of the CUD (hand-field relationship) when the hands are placed in crossed positions (Brebner et al. 1972; Riggio et al. 1986; Wallace 1971). Such large CUD values, in choice or go/no-go RTs, are rather spatial-compatibility effects based on same- versus opposite-side relationships between the stimulated visual field and the response key and are attributed to stimulus-response (SR) coding overlap. Simon et al. (1970) proposed that this effect corresponds to a natural tendency to react toward the major source of stimulation. This effect has been long considered to be an automatic process occurring independently of the subject's intentions, and typically even without any awareness (Kornblum et al. 1990).

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Spatial compatibility in simple RT

Several studies investigated the eventuality of spatial compatibility with simple RT by comparing crossed-hand to uncrossed-hand conditions. No spatial-compatibility effect was obtained, either when a visual field was fixed within blocks (Anzola et al. 1977; Berlucchi et al. 1977) or when it varied randomly (Aglioti et al. 1991), suggesting that SRT implementations of the Poffenberger paradigm are immune to spatial compatibility and thus really do index IHTT exclusively.

This lack of modulation of the CUD by the relation between the location of the stimulus and the response key is consistent with Hommel's (1996b) proposal that responses triggered from simple detection are usually immune to spatial-compatibility effects because they are released *before* the establishment of a spatial code for the stimulus capable of interacting with the spatial code for the response. That simple RT would never produce spatial-compatibility effects is not true, however. Hommel (1996b) could produce consistent spatial-compatibility effects in simple RT situations, especially when two response codes had to be simultaneously maintained. A 31-ms SRT advantage for the compatible hand-field conditions was produced when each detection trial was preceded by a visual indication of which key to use for the next target. That the response was not always fully prepared before stimulus delivery is evidenced by significantly more key errors in the incompatible than in the compatible conditions (i.e., more errors in pressing the key ipsilateral to the stimulus when the other key was requested). In another experiment, an occasional different stimulus was presented at fixation immediately after the key release following the response to a standard lateralized stimulus. The group responding to that occasional stimulus with the same hand as for the lateralized stimuli (i.e., with only one hand responding in a large block of trials) yielded a 3-ms CUD while the group using the other hand for the occasional centered stimuli yielded a 20-ms advantage of the ipsilateral field in signaling the standard lateralized stimuli. The latter condition, however, is barely one of simple RT, being distinguished from a choice reaction-time paradigm only by the timing relationship with the previous release of the response key: if the central stimulus does not appear immediately, the next stimulus will be lateralized and will require this 'preset' response. In a third experiment, a standard Poffenberger paradigm in which the responding hand alternated by blocks of 8 or by blocks of 80 trials yielded an average 5.5-ms advantage for compatible hand-field combinations, with the 7-ms effect for frequent hand alternation not differing from the 4-ms effect for blocks of 80 trials (except in the later quintiles). Two other experiments used responses of the right hand only, with the index and middle fingers, and showed key-field compatibility effects (16 ms in one study but only 1 ms for the same condition among three other conditions in the other study, possibly an effect of practice on the compatibility effect; the overall compatibility effect in the latter study was 5.25 ms). Godbout et al. (1995) obtained a significant similar effect of this kind with a trial-by-trial response code alternation (1995) compared to large blocks of trials without alternation of the response code. In Hommel's (1996b) experiments, the spatial-compatibility effect was larger for slower responses (when the individual RTs of each condition were classified by quintile), presumably because the spatial code associated with the stimulus had time to establish and either facilitate or oppose response initiation. Clearly, simple RTs can produce spatial-compatibility effects, and so we agree with Hommel (1996b) that it therefore remains to be demonstrated that the concept of IHTT is at all necessary in individuals with an intact corpus callosum. We report a series of experiments designed to clarify and delineate mechanisms of spatial compatibility in SRT.

Methodological generalities

All statistical analyses consisted of repeated measures ANOVAs, with an alpha criterion set at .05, one-tailed for oriented experimental hypotheses, two-tailed for exploratory hypotheses (only one-tailed tests will be specified as such). All analyses of RTs were carried out on the quintile medians of error-free trials for each subject in each condition. Following Hommel (1996b), the compatibility (and other) effects in SRT were analyzed by quintile, because this can provide support for spatial-compatibility effects. Some studies involved periliminal stimuli while others used easily detectable stimuli. In all experiments, indices of kurtosis and skewness indicated normality, but because the postulate of sphericity for repeated measures was not always perfectly respected, the Greenhouse-Geisser adjustment was always applied to the degrees of freedom for analyses involving more than two levels of a variable (when this applies, the degrees of freedom reported are the adjusted ones). All studies had equal numbers of males and females, age and education matched. Sex was actually used as a between-subject variable, but it produced no consistent pattern (the few significant interactions involving sex could be attributed to the expected share of type 1 errors), and no effect involving sex is reported to simplify the statistical reports. The presence of sex in the analyses will only be visible in the degrees of freedom reported. Errors were analyzed but inference tests did not yield sufficient power to warrant report. Ethical authorization certificates were given by the Université du Québec à Montréal's ethics committee for all the projects reported.

Experiment 1

Introduction

Experiment 1 is essentially a replication of the study reported by Godbout et al. (1995; see Braun et al. 2003 for details) comparing the CUD in three SRT conditions labeled "alternating keys", "alternating hands" and "three press". It was meant to confirm the unusually large CUD (14 ms) observed in the alternating-hands condition for a SRT task (at a time where it was generally accepted that simple RTs do not produce spatial-compatibility effects) and constituted a second attempt to demonstrate CUD reduction (−1 ms) with an increased response requirement (the three-press condition). As in Godbout et al. (1995), stimulus contrast with the background was adjusted for each subject to produce about 30% omission errors overall. In distinction to Godbout et al. (1995), several conditions and analyses were introduced here to clarify and delineate possible spatial-compatibility effects. For example, in one condition, subjects were required to alternate responding index fingers at each trial (similar to Hommel 1996b, but more frequently). In the other two conditions, subjects were required to alternate responses (within a large block of trials with one index finger) between two keys placed side by side, similarly to Hommel (1996b), but involving only one responding finger instead of two. This particularity was introduced as a control for the eventuality that any right/left alternation of effectors could favor spatial-compatibility effects. With this design, an outstanding CUD in the alternating-hands condition would be interpretable as due to hemisphere-dependent spatial compatibility rather than a purely cognitive effect. We reasoned that previous authors (cited above) failed to obtain spatial-compatibility effects in simple RT because they did not require alternation of responding fingers or keys. Of course, Godbout et al. (1995) and Hommel (1996b) presumably did obtain spatial-compatibility effects because they*did* introduce right/left response alternation.

Method

Subjects

Nine female and nine male university students (20–34 years of age) signed a consent form and were paid to volunteer. They had to be free of substance abuse, neurological or psychiatric history and visual problems (assessed by the Optec Vision Tester, model 2000, Stereo Optical Co., Inc.), and be right-handed (assessed by the unpublished Collin and Braun 1996 scale of hand dominance).

Procedure

Experimentation was done in ambient lighting of 0.3 cd/m^2, using a 400 MHz Pentium PC with a Mitsubishi Diamond Pro 15F5 color monitor and a Mach64 ATI graphics card. The screen background was blue (maximum blue intensity with null red and green components) producing a luminance of 9.9 cd/m^2. To minimize the risk of stray light dispersion, the stimuli were darker patches of the same hue. They were 6×6-mm squares of the same hue as the background, dithered with various portions of black pixels. Their inner border was 6.86° to the left or right of center. They were presented for 80 ms.

It can be observed that computer monitors do not display perfectly symmetrically pictures that are nominally symmetrical at the level of their pixel composition. In particular, a fixed number of pixels tend to produce a different width near the left and right edges of the screen, and even constant nominal intensity tends to vary across screen positions (see Ratinckx et al. 2001). The inner edge coordinates of the stimuli were adjusted to produce equal left and right distances from fixation, but the same dithered square was used bilaterally. To neutralize the remaining screen asymmetries, half the trials were presented directly while half were reflected (producing a right/left inversion) by a Mirolux mirror with the reflecting surface on the face rather than on the back of the glass (to prevent phantom reflections). The mirror formed a 45° angle with the screen in the horizontal plane; the subject looked at it from the side of the monitor. When the mirror was present, the computer program presented the left-visual-field stimuli to the right of the screen and vice versa. The subject's head was enclosed in a flat black containment apparatus (tunnel) to preclude extraneous light and minimize reflections from the screen itself. Eyes were 79 cm from the screen, the forehead resting against a stopper, and the chest was 15 cm from the response key. Grey cross hairs at center screen and eye level formed a constant fixation point. The response-to-stimulus interval was pseudorandom between 1,000 ms and 2,500 ms, following an exponentially decreasing probability distribution (mean = 1,276 ms). The field of stimulation was selected randomly. The task consisted of a key press upon detection (simple RT). Only responses occurring between 150 ms and 750 ms from stimulus onset were accepted as valid, but an omission error required that no response was emitted within 1,200 ms from stimulus onset. In the three-press condition, the RT was that of the first key press, and the subject was required to press the key three times within 600 ms. If there were more or fewer than three presses, a key-press error was coded and the subject informed by beeps (one for a single press, two for two, four for four, etc.). In all cases of error, the trial was replaced. To obtain our objective of a 30% omission-error rate, an automatic adjustment of the stimulus distinctiveness was started prior to data collection, during practice trials, and continued throughout the experiment by evaluating the overall detection rate for each consecutive set of 20 trials. If there were too many omissions, a more easily detectable stimulus with a larger proportion of black pixels was substituted, and vice versa if there were too few omission errors. The set of dithered squares contained 12 levels: from very easy, at 7.6 cd/m^2, to very hard, at 9.4 cd/m^2. Instructions as to the hand to be used were displayed on the screen for at least 1,000 ms, as were error feedback messages concerning key-alternation errors (which hand to restart with). The messages were displayed mirror-reversed on the screen when the mirror was present. A key press terminated the display of the messages and restarted the experimental routine.

In the three conditions, the contiguous B and N keys of the QWERTY keyboard configuration were used for responding. The rest of the keyboard was masked by a piece of cardboard to facilitate key localization without looking. In the alternating-keys condition, the subject responded with an index finger press but changed keys after each response. In the alternating-hands condition, the subject changed index fingers after each response but pressed the left key with the left index and the right key with the right index. In the three-press condition, the subject changed keys, as in the alternating-keys condition, for each trial, but was required to provide three key presses within 600 ms poststimulus onset on the same key. The non-responding hand was placed on the subject's lap (i.e., at the meridian) except for the alternating-hands condition, in which the index finger of each hand rested on its own key. Starting hand, mirror/non-mirror, alternating-keys/Alternating-hand/three-press conditions were blocked in counterbalanced fashion (Latin square). Altogether, there were 24 uninterrupted series of at least 80 error-free trials for each hand and task (minimum 3,840 correct RTs overall), preceded by 100 practice trials. All trial series ran uninterrupted until 40 error-free trials were available for each key and each visual field (i.e., four series with each hand in the alternating-keys and three-press conditions, and eight series with both hands in the alternating-hands condition). As in most previous research with this paradigm, fixation was not verified, but was assured by random distribution of the stimuli on each side of the fixation point and by repeated explicit instructions to fixate the cross hairs at all times. When eye movements were monitored in this type of simple RT paradigm, they were always found to be negligible (see Braun et al. 1995).

Results

Anticipation-error frequencies were 2.1% in the alternating-keys condition, 1.7% in the alternating-hands condition and 0.9% in the three-press condition. The key-press error rate in the three-press condition was 3.4%. Failure-to-alternate errors occurred at rates of 0.9% in the alternating-hands condition, 0.2% in the alternating-keys condition, and 0.4% in the three-press condition. The omission-error rates were 33.1% in the alternating-keys condition, 34.0% in the alternating-hands condition and 35.4% in the three-press condition.

Reaction times

The main analysis for RTs was a 2×2×3×5 univariate repeated measures ANOVA (Field, Hand, Condition, Quintile) on median quintile RTs, where the responses on the two keys in the two single-hand conditions were pooled. The first effect of interest consists of determining whether the experimental conditions influenced RT. The main Condition effect was significant ($F_{(adj\ 1.4,32)}=14.1$, $p<0.0005$), the alternating-hands condition (425.9 ms) being significantly faster than both the alternating-keys condition (432.4 ms; $F_{(1,16)}=4.73$, $p<.046$) and the three-press condition (452.5 ms; $F_{(1,16)}=20.13$, $p<0.0005$). The difference between the latter two was also significant ($F_{(1,16)}=14.83$, $p<0.002$). In the Poffenberger paradigm, spatial compatibility and interhemispheric transfer time are indissociably niched within the Field × Hand interaction (CUD). Our expectation regarding CUD, based on Godbout et al. (1995), was for a positive CUD for the alternating-keys and Alternating-hand conditions and a reduced, perhaps slightly negative, CUD for the three-press condition (see Table 1 for results). The global Field × Hand effect was specified as two-tailed. This effect was significant ($F_{(1,16)}=12.9$, $p=0.002$) and, as expected, it was modified by further interaction with Condition ($F_{(adj\ 1.5,25)}=12.7$, $p<0.0005$). See Table 1.

Recall that Hommel (1996b) argued that the lengthening of CUDs in later quintiles of simple RTs is indicative of spatial compatibility (the spatial code for the stimulus having more chance to interfere with the spatial code for the response when the delay between detection and response is longer). The Field × Hand × Quintile effect was significant ($F_{(adj\ 1.9,31)}=3.4$, $p<.016$). The CUDs per quintile were 5.0, 5.3, 4.2, 4.7 and 6.0 ms. This effect was not significantly linear (it was significantly quadratic). The Field × Hand × Condition × Quintile interaction was also significant ($F_{(adj\ 3.5,\ 128)}=4.5$, $p<.0005$). The only significant trend was the cubic ($F_{(1,16)}=24.2$, $p<.001$).

There are potentially two types of spatial-compatibility effects in this experiment, one *between hands* and another *within hand*. The alternating-hands condition comprises spatial compatibility when a hand responds to an ipsilateral stimulus. Since that hand has just taken over response preparation from the other hand, this can also be considered a *between hemispheres* situation (both hemispheres are surely involved in changes in the response code during response preparation). The "alternating-keys"

Table 1 Quintile means of RTs (ms) as a function of stimulated Field and responding Hand in each of the three experimental conditions (error-free trials only) (N=18)

Conditions	Left hand		Right hand		CUD
	Left field	Right field	Left field	Right field	
Alternating-hands	427.31	438.28	439.82	424.58	13.10***
Alternating-keys	419.02	431.38	424.89	428.23	4.51*
Three-press	450.94	455.11	452.11	451.64	2.32

*p<.05, ***p<.001 (one-tailed tests)

and "Three press" conditions comprised spatial compatibility not only when the hand and stimulus were ipsilateral (as for the alternating-hands condition), but also, and independently of hand and stimulus, when the *key* selected to respond was ipsilateral to the stimulus. This can be considered a form of *within hemisphere* compatibility (since responses are solicited from the same hand, over large blocks of trials, one could presume that the hemisphere contralateral to the solicited hand is primarily involved in changes in the response code imposed by key alternation). Whereas in the ordinarily implemented Poffenberger paradigm spatial compatibility cannot be disentangled from interhemispheric relay time, in the present implementation it can be. The two blocked-hand conditions (alternating-keys and three-press) allowed examination of a Field-Key compatibility effect within a 2×2×2×2×5 Field, Hand, Condition, Key, Quintile repeated measures ANOVA. The Key factor did not interact significantly with the Field or Condition factors. However, the Key × Hand interaction was significant ($F_{(1,16)}$=7.8, p<.014). The Key × Hand × Quintile interaction was also significant ($F_{(4,38.7)}$=4.7, p<.012) and this consisted principally of a linear trend ($F_{(\mathrm{adj}\ 4,38.7)}$=9.5, p<.008). There were no other significant effects involving the Key factor. See Table 2.

To determine whether *between hands* spatial compatibility presents a clearer pattern of effects when devoid of *within hand* changes in the response code, a 2×2×5 repeated measures ANOVA was applied to RTs in the alternating-hands condition only. Though the Field × Hand interaction was highly significant (see Table 1), the Field × Hand × Quintile interaction was not and presented no linear or other trend.

Discussion

This experiment was a replication of Godbout et al. (1995). In particular, it replicated the near-14-ms CUD when responses alternated from one hand to the other on a trial-by-trial basis. The CUD for the condition of responses by three presses in rapid succession on the same key was again not significantly different from zero. In this experiment, we obtained several significant effects interpretable as an interhemispheric relay cost (significant Field × Hand interactions). A cognitive factor, certainly attentional, must be inferred from the significant Field × Hand × Condition interaction (interhemispheric relay costs are supposed to be constant, i.e., unaffected by cognitive manipulations). Indeed, the longer CUD was present in the alternating-hands condition, a condition resembling Hommel's Experiment 3, wherein he laid a good claim for a spatial compatibility effect. Furthermore, the Key × Hand interaction, and the linear Key × Hand × Quintile interaction, are best interpreted, we think, as a spatial-compatibility effect: the right hand favoring the right key and the left hand favoring the left key. That this effect should increase linearly as a function of quintile also fits with what is expected of a spatial-compatibility effect (Hommel 1996b). As for the interactions involving the Field × Hand × Quintile terms, we have no interpretation to propose since they departed from linearity.

Table 2 Quintile mean RTs (ms) as a function of Key, Hand and Quintile (error-free trials only) (N=18; *Ihkca* ipsilateral hand/key condition advantage)

	Left hand		Right hand		Ihkca
	Left key	Right key	Left key	Right key	
1st quintile	333.3	334.6	340.6	338.9	1.8
2nd quintile	383.8	385.7	390.5	390.3	1.1
3rd quintile	425.1	427.2	430.8	429.6	1.7
4th quintile	471.3	477.3	480.9	478.4	4.3**
5th quintile	561.0	567.7	573.5	562.5	8.9***

**p<.01, ***p<.001 (one-tailed tests)

Experiment 2

Introduction

This experiment was designed to further explore spatial compatibility in conditions of *varying* motor preparation of one hand. Hommel (1996b) demonstrated in his Experiment 1 that he prolonged general SRT (relative to an experiment reported in Hommel 1995) by cueing the hand required to respond after stimulus onset (with a central arrow). He also obtained a grand CUD of 31 ms, which was highly significant and which significantly increased as a function of Quintile. Braun et al. (1995) also used a pre-stimulus central arrow cue in the Poffenberger paradigm, orienting attention to valid (i.e., probable) versus invalid (improbable) stimulus locations. This manipulation failed to reliably influence CUDs. Taken together, the Hommel (1996b) and Braun et al. (1995) experiments suggest that it is manipulation of preparation for the location of the *response*, not of preparation, for *stimulus* location, that influences the CUD, and when that is the case, it is the spatial-compatibility component of the CUD that is affected. The next experiment was designed to determine whether varying demand on response preparation by other means would correspondingly influence spatial compatibility. More specifically, does increased response preparation, independently of forced recoding of response *location*, influence the CUD? We had observed a non-significant decrement of the CUD in the three-press condition of Experiment 1 and wondered whether we could produce it more reliably. We also included a cognitive spatial compatibility component (variation of Key × Field conditions), independent of the anatomical component believed to generate CUDs (variation of Field × Hand conditions), as in Experiment 1, to determine whether either could stand alone. Finally, we were intrigued to determine whether increasing Preparation Load would interact with any Field × Key spatial compatibility effect.

Subjects

Nine male and nine female experimentally naïve university students (19–27 years of age) were selected and tested using the same inclusion/exclusion criteria and modalities as the previous experiment.

Procedure

The procedure was the same as the three-press condition of Experiment 1 except for the following changes: Instead of being required to press the response key three times in rapid succession, the subject was required to fixate the central fixation cross, wait for it to be replaced by a number from 1 to 5 (ASCII character displayed for 500 ms), and then upon display of a lateralized stimulus, press the response key the number of times corresponding to the previously centrally displayed number, in as rapid a succession as possible. The interval from number display offset to stimulus onset varied from 500 to 1,500 ms (mean = 825 ms). The interval from response termination (the last press of the required series) to number display onset was 1,500 ms. The time allotted to complete the presses was 350 ms, 600 ms, 850 ms and 1,100 ms from the first press for two, three, four and five presses respectively. The same centrally presented number could not appear on two consecutive trials, but the number otherwise varied randomly after each response. When the number disappeared, the central cross hair replaced it until the next number display. For this experiment, keyboard response keys were replaced by Lafayette telegraphic keys which were each adjusted for contact at 170 g and each placed one inch from midline. This ensured an optimal balance for crisp response sequences and also great equivalence of the keys for speed, excursion and resistance. The key contacts were fed to the two mouse-key ports. The requirement of alternating fingers (and thus keys) at every trial remained identical to that in Experiment 1. The total number of error-free trials was 960, preceded by 60 practice trials with each hand. Because pilot data indicated that the task was too difficult and RTs too variable for several subjects, the automatic adjustment of stimulus distinctiveness was abandoned, and the screen background luminance was set at 2.9 cd/m^2 and the stimulus luminance at 1.6 cd/m^2.

Results

The overall omission-error rate was 0.3%. The anticipation-error rate was 2.4% and the key-press error (i.e., too many or too few presses) rate was 6.9%. The rate of alternation errors was 0.2%.

Reaction times

In the present experiment, the low omission-error rate, due to greater distinctiveness of the stimulus and background, was paralleled by much briefer RTs than those of Experiment 1.

A 2×2 × 2×5 × 5 repeated measures ANOVA comprised Field, Hand, Load, Key and Quintile within factors. The dependent measure was quintile RTs. The Load factor refers to the number of key presses required. In this experiment this experimental manipulation comprised five levels (one to five presses being conceivably equivalent to a linear increase in motoric preparation load). The effect of Load on RT was significant ($F_{(\text{adj } 1.4,22.2)}=19.4$, $p<0.00005$, one-tailed test), and each increment in the number of required key presses significantly prolonged the RT as determined by one-tailed post hoc tests (except the four- to five-press increment). Error-free mean quintile RTs at each (increasing) Load condition were 275, 295, 301, 306 and 303 ms.

The Field × Hand interaction was significant ($F_{(1,16)}=23.9$, $p<0.0001$, one-tailed test). The Field × Hand × Load interaction fell far short of significance, and manifested no trend at all in support of the hypothesis of a monotonic effect of Load on CUDs. CUDS at increasing loads were 1.6, 4.8, 3.3, 4.1 and 3.5 ms. In fact, the only effect of increasing Load on RT was from one press to two, an effect mirrored in the CUDs. The Quintile factor did not interact significantly with any other factor.

The Field × Key interaction was significant ($F_{(1,16)}=13.5$, $p<0.002$, one-tailed test), and the distribution of the RTs clearly indicates that the right-sided key favored the right hemifield while the left-sided key favored the left hemifield (see Table 3). No other interaction involving Key reached significance (see Table 3).

Since there are points of resemblance between Experiments 1 and 2, namely a one-press condition and a three-press condition, in each, we tested the inference of a Field × Hand × Experiment interaction and of a Field × Key × Experiment interaction. Of course, Experiment 2 comprised more easily detectable stimuli, thus shortening general RT. The general RTs in the "one press" conditions in Experiments 1 and 2 were 432 and 281 ms respectively. The general RTs in the three-press conditions in Experiments 1 and 2 were 452 and 308 ms respectively. Neither of the two tests of the Field × Hand × Experiment

Table 3 Quintile mean RTs (ms) as a function of Hand, Key and Field (error-free trials only) (N=18; *Ifkca* ipsilateral field/key condition advantage)

	Left field		Right field		Ifkca
	Left key	Right key	Left key	Right key	
Left hand	298.42	304.70	311.04	306.26	5.53**
Right hand	297.58	304.91	302.61	300.12	5.07**

**p<.01 (one-tailed tests)

interaction reached significance (as in Braun et al. 1996), and neither of the two tests of the Field × Key × Experiment interaction reached significance either.

Discussion

The significant effect of motoric preparation Load on RT observed here was very similar to the finding of Garcia-Colera and Semjen (1987). The increase in RT was absent from four to five key presses. Garcia-Colera and Semjen (1987) also observed that, at very high levels of increasing motoric preparation load, RT was no longer influenced. An additional problem with our attempt to manipulate response preparation was the following: subjects probably distributed some of the response preparation, in time, on each side of stimulus occurrence. In other words, they probably pressed the response key as fast as they could once and then completed the formatting of the rest of the response sequence. If this in fact occurred, then our presumption of increasing response *preparation* prior to stimulus detection could have been unfounded.

In this experiment we observed a spatial-compatibility (Key × Field) effect, of a magnitude similar to the CUD itself. This effect was not modulated by the number of key presses. The importance of the S-R spatial map, and especially of its motor component, in simple RT was confirmed by this experiment, replicating Hommel (1996b). Indeed, the Field × Key effect observed is orthogonal to the Field × Hand interaction, the former being attributable only to spatial compatibility and the latter to any combination of anatomical and/or spatial compatibility. The spatial-compatibility effect was not modulated by stimulus Luminance or motor Preparation Load and was not more manifest in later quintiles. As suggested by Hommel (1996b), the Field × Key effect could have been due to rapid alternation or change in S-R spatial coding demands (i.e., Key alternation). Furthermore, this experiment, together with Experiment 1, suggests that manipulation of response contingencies in SRT significantly affects the CUD, and significantly induces spatial compatibility, only when the *spatial* response code is manipulated, independently of other demands on response preparation. More specifically, considering that increased load non-significantly prolonged the CUD in Experiment 1 and non-significantly shortened the CUD in Experiment 2, we are forced to conclude that there are no grounds to believe that manipulation of response preparation (limited to trials blocked at the variably loaded hand) has any real effect on either interhemispheric dynamics or spatial compatibility.

In Experiments 1 and 2, the CUD (Field × Hand interaction) was highly significant and was not modulated by Luminance, Preparation Load or Quintile, just as would be expected of a simple relay-time effect, suggesting robust presence of an interhemispheric transfer-time effect.

Experiment 3

Introduction

Spatial-compatibility effects are most convincingly revealed by comparing normal (lateral) hand positions (yielding positive CUDs) with crossed-arms (one arm over the other) positions (yielding negative CUDs when due to ipsilateral compatibility) (Riggio et al. 1986). Experiment 3 was designed to further delineate (characterize) the prolongation of the CUD observed in the alternating-hands condition of Experiment 1, to further solicit the spatial-compatibility effect within that particular design, and to disentangle it from interhemispheric relay time. To attain this objective, we implemented the alternating-hands condition of Experiment 1, but with a twist: instead of having the responding hand placed in a central (meridianal) position, side by side, both hands were to be placed in a central position (as in Experiment 1) side by side, or a central position with crossed arms, or a lateral position side by side, or a crossed-arms position. If a spatial-compatibility effect in the uncrossed-arm position adds to IHTT and/or other interhemispheric costs (we call these anatomical-compatibility effects), it ought to reduce these by a corresponding amount in the crossed-arm condition. The average CUD of both arm positions is then a proper estimate of the CUD intended to estimate IHTT. Because lateral hand placement makes stimulus and hand placement closer, and thus more compatible, we expected the lateral hand placement to increase the effect of spatial compatibility compared to having the hands close to the meridian. In this experiment, Key alternation was not implemented. Although this could have been the case (the subject would have alternated between four response keys), we felt that such complexity was unnecessary, since spatial compatibility could clearly be inferred from the relation between the crossed- and uncrossed-hands conditions.

Subjects

Eight male and eight female experimentally naïve university students (18–25 years of age) were selected and tested using the same inclusion/exclusion criteria and modalities as the previous experiment.

Procedure

The procedure was the same as the alternating-hands condition of Experiment 1, except for the following changes: Blocks of trials replicated the "alternating-hands"alternating-hands condition of Experiment 1 (a quarter of the blocks) using the F6 and F7 keys of a back-facing keyboard with each index finger on its "normal" side. Other blocks required the subject to place one finger over the other (i.e., crossing the meridian; a quarter of the blocks). The subject was required to cross the fingers at the most distal joint (keeping the fingers as straight and parallel as possible). In other words, the subject used the same keys, but with the fingers on the opposite keys. Another condition placed the hands further apart on the keyboard (the F3 and F10 keys of the same back-facing keyboard) with the right index finger on the right and the left index finger on the left (a quarter of the blocks). Finally, a fourth condition placed the left index finger at the right extremity (the F3 key of the back-facing keyboard) and the right index finger at the left extremity (the F10 key of the back-facing keyboard). In this condition, the arms were crossed between the wrist and the elbow. The keyboard was placed back-to-front to avoid other keys being touched by the subject's hands. The hand over the other hand (or finger over the other finger) was counterbalanced for the crossed-arms conditions (i.e., half the subjects had their left hand or finger over the right and the other half had the right over the left). In all conditions, the subject was required to alternate responses of the left and right hand from trial to trial. The four hand-position conditions followed an ABCDDCBA sequence to cancel linear practice effects. There were 80 uninterrupted error-free trials per run, 40 per field (total = 640 trials) preceded by a practice run of 80 trials. The response-to-stimulus interval varied from 1,000 to 2,500 ms with a mean of 1,487 ms.

It is important for the reader to understand that, in defining the term CUD, the designation of the Hand corresponds to our everyday understanding, and not its location in space. The latter is referred to as the Key. Thus the Field × Hand effect corresponds to a CUD and reflects the difference between an ipsilateral and a contralateral pathway, unless Field and Hand further interact with Position (i.e., crossed versus uncrossed hands). A Field × Hand × Position interaction is thus a spatial-compatibility effect.

Results

The overall rate of anticipation errors was 1.0% and the rate of alternation errors was also 1.0%. The overall percentage of omission errors was 31.9%.

Reaction times

A 2×2×2×2×2×5 repeated measures ANOVA was carried out on quintile RTs. Factors were Field, Hand, Eccentricity (centrally versus laterally emplaced keys), Position (crossed versus uncrossed arms), Superimposition (left limb over right versus right limb over left: a *between subjects* effect not reported in the following text) and Quintile. The Eccentricity main effect was not significant ($F_{(1,14)}$=3.1, p<.11). The Position main effect was just barely significant ($F_{(1,14)}$=3.2, p<.045, one-tailed test). Our critical test of the existence of spatial compatibility, the Field × Hand × Position interaction, was significant ($F_{(1,14)}$=11.5, p<.002, one-tailed test). The global CUD was indeed positive (+4.2 ms) and corresponding Field × Hand interaction was significant ($F_{(1,14)}$=2.1, p<.05, one-tailed test). In other words, spatial compatibility is unable to explain all the CUD variance; some of it is best explained as IHTT. There were no significant interactions involving Eccentricity. See Table 4.

The Field × Hand × Quintile interaction was not significant. However, the Field × Hand × Position × Quintile interaction was significant ($F_{(\text{adj } 1.98,27.8)}$=3.2, p<.03, one-tailed test, based on requirement of a positive linear trend). The trend was indeed positive and linear ($F_{(1,14)}$=5.6, p<.05). The nature of this interaction was as expected from Hommel (1996b) and is depicted in Fig. 1.

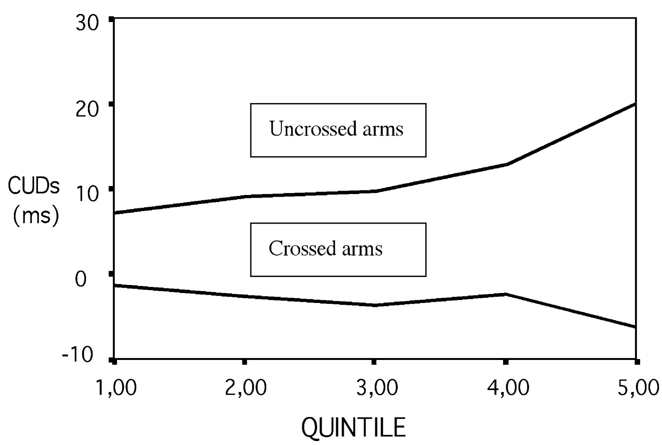

Fig. 1 Simple reaction time differences between crossed and uncrossed hand-field conditions as a function of quintile in Experiment 3

Table 4 Quintile means of RTs (ms) in each combination of Field and Hand and CUDs (ms) as a function of hand positions (error-free trials only) (*N*=16; *CUD* crossed/uncrossed difference)

Eccentricity/Position	Left hand		Right hand		CUD
	Left field	Right field	Left field	Right field	
Central/uncrossed arms	427.59	441.04	432.94	428.88	8.75*
Central/crossed arms	446.21	423.19	443.85	429.89	−4.53
External/uncrossed arms	436.11	436.31	449.82	420.49	14.77**
External/crossed arms	445.39	447.92	437.13	443.55	−1.95

*p<0.05, **p<.01 (one-tailed tests)

The other interactions involving Field and/or Hand and Quintile were not significant.

Considering that in the crossed-arms conditions, the spatial-compatibility advantage (or effect) is in the direction opposite to IHTT, and that in the uncrossed-arms conditions they are in the same direction, it is thus possible to extract specific components by subtraction or addition (this assumes that the spatial compatibility is the same whether the hands are crossed or not). We designate the *spatial compatibility* component as consisting of (CUD values in the uncrossed arms condition *minus* CUD values in the crossed arms condition)/2. The test that this value differs from zero is the Field × Hand × Position interaction. We designate the *anatomical compatibility* component (an adjusted IHTT estimate) to consist of (CUD values in the uncrossed arms condition *plus* CUD values in the crossed arms condition)/2. The test that this value differs from zero is the Field × Hand interaction. See Table 5.

Discussion

This experiment further demonstrates significant presence of spatial compatibility in simple RT (the significant Field × Hand × Position interaction). The significant Field × Hand × Position × Quintile interaction supports Hommel's (1996b) proposal to the effect that longer RTs reflect more late-stage interference between the stimulus and the response spatial location codes.

The juxtaposition of the crossed- and uncrossed-hand positions in this experiment had an additive effect: spatial-compatibility and -incompatibility effects both increase weakly with each quintile (thus the non-significant Field × Hand × Quintile interactions in all three experiments), but the difference between the crossed- and uncrossed-hand conditions is approximately double the result when each one is taken individually, thus the significant Field × Hand × Position × Quintile interaction of the present experiment (see Fig. 1). Eccentricty of hand emplacements did not contribute any systematic variance to RT at all.

However, this experiment also demonstrates presence of a robust interhemispheric transfer-time (IHTT) effect other than spatial compatibility (the significant Field × Hand interaction, not modulated by Quintile, as would be expected from simple anatomical relay time).

Experiment 4

Experiments 1, 2 and 3 demonstrated presence of significant spatial compatibility in simple RT. This finding could very plausibly, it seemed to us, be explained by our introduction of finger or hand alternation in these tasks. Because we obtained a reliable spatial-compatibility effect in Experiment 3 with alternation of the responding hand on a trial-by-trial basis with fingers in central location, a location resembling the rest of the literature (meridianal key), we elected to limit ourselves to this condition in order to test its characteristics further with a special manipulation. We sought to further characterize the particular spatial-compatibility effect by manipulating the nature of the alternation. Hommel (1996b) obtained very variable results when he considered blocking the between-key alternations. Blocks of 8 or 80 responses with the same key produced CUDs of 7 and 4 ms respectively that did not differ significantly (except in the last quintiles). With alternation confined to the right hand (finger alternation), with blocks of 80 trials using the same finger, a spatial-compatibility effect of 16 ms was obtained, but this effect did not replicate (1 ms was obtained in the replication). We reasoned that if that spatial-compatibility effect is primarily or exclusively due to trial-by-trial responding-hand alternation (i.e., if it is transient), then it should disappear (or diminish) within a very small block of trials (e.g., 3) with the same hand, and reappear (or be enhanced) on the next trial requiring alternation of the responding hand. Such an effect would demonstrate that the CUD in simple RT can at least be partly attributable to a form of spatial compatibility during a very brief focussing of attention on the S-R code (i.e., reprogramming of the response code for a given trial). In other words, we were interested in disentangling two eventualities: (1) spatial compatibility in SRT derives from nothing other than reduced interference of stimulus and response codes (i.e., compatible fields and hands); and (2) spatial compatibility in SRT is modulated by shifts of attention (presumably response preparation) imposed by the requirement of a rapid change of effectors (in the present case, responding hand) while performing the task. Such an effect would be akin to the attentional shift described by Kinsbourne (1970) in which focussing on one body side (e.g., by response selection under time pressure) inhibits attention to the other body side. Although apparently complex, the Field × Hand × Position interaction is simply the spatial-compatibility effect. The attentional-shift interpretation specifically predicts that the spatial-compatibility effect should be larger at rank one

Table 5 Decomposition of CUDs as a function of estimated *anatomical compatibility* (adjusted IHTT estimates) and *spatial compatibility* components in quintile mean reaction times (N=16)

Eccentricity	Anatomical-compatibility component (adjusted IHTT index)	Spatial-compatibility component
Central (reaction times)	2.11	6.64**
External (reactions times)	6.41*	8.35*

*p<.05, **p<.01 (one-tailed tests)

than at ranks two and three combined. Accordingly, the Field × Hand × Position × Rank interaction will be treated as a one-tailed effect contingent on the means showing this predetermined pattern. On the other hand, if the spatial-compatibility effect is stable and has only to do with an inert spatial-motor map, the effect should not be modulated by the rank of the response within a half cycle of alternation, which constitutes the null hypothesis of this four-factor interaction.

Subjects

Eight male and eight female experimentally naïve university students (19–25 years of age) were selected and tested using the same inclusion/exclusion criteria and modalities as the previous three studies.

Procedure

This experiment was identical to the central conditions of Experiment 3 except for the following: Instead of changing the responding index finger on every trial, subjects were required to press a response key with one index finger for three consecutive responses and then to change the responding hand for another three responses, and so forth. A 200-ms beep (1,000-Hz tone) indicated to the subject that it was time to change the finger (and key) for his or her next response. An uninterrupted trial run comprised 60 error-free trials (10 per field at each rank on each key; 8 runs with hands crossed and 8 with hands in normal position: total 960).

Results

The overall rate of anticipation errors was 0.7%. The rate of alternation errors was 0.7%. The overall rate of omission errors was 31.1%. A 2×2×2×3×5 repeated measures ANOVA on quintile RTs was carried out. Within factors were Field, Hand, Position as in Experiment 2, Rank (the first of a series of three responses with a given hand, the second and the third) and Quintile. The new experimental variable introduced here, namely Rank, had a powerful effect on RTs ($F_{(adj 1.1,28)}=50.0$, $p<0.0001$). Mean RTs were 454, 431 and 432 ms as a function of Rank. The main effect of arm Position was again not significant. There were four significant interactions involving Field and Hand, namely the Field × Hand interaction ($F_{(1,14)}=6.5$, $p<.013$, one-tailed test), the Field × Hand × Position interaction ($F_{(1,12)}=11.9$, $p<.003$, one-tailed test) and the Field × Hand × Position × Rank interaction ($F_{(\mathrm{adj}\ 1.8,25.11)}=2.8$, $p<.04$, one-tailed test) and the Field × Hand × Position × Quintile interaction ($F_{(\mathrm{adj}\ 1.8,24.3)}=10.4$, $p<.0001$, primarily linear trend ($F_{(1,14)}=15.1$, $p<.002$). This effect, depicted in Fig. 2, was as expected from Hommel (1996b). No other interaction involving Quintile reached significance. All interactions involving Field × Hand were more marked, and thus contributed more, than the CUDs at the left than at the right hand (see Table 6). It has long been known that in SRT directional CUDs differ, i.e., left-to-right hemisphere CUDs (collected at the right hand) are shorter (closer to zero) than their left-hand counterparts (Marzi et al. 1991; Braun et al. 2003).

We decomposed CUDs as a function of estimated *anatomical compatibility* (adjusted IHTT estimates) and *spatial compatibility* components in reaction times as in the previous experiment. See Table 7.

Discussion

With a choice RT task, Rogers and Monsell (1995, Experiment 6) had subjects change an aspect of the response code at every fourth trial. The same type of RT profile as in the present experiment was observed. The RT was much greater at trial 1 than the others, which did not differ from each other. Obviously, changing a response code while on line (under time pressure) is not benign (i.e., there is a substantial cost).

Presence of spatial compatibility was again clearly demonstrated in this experiment. The pattern of the spatial compatibility as a function of RANK showed a reduction from rank 1 to the following ranks, as anticipated for a temporary attentional effect associated with shifting the responding finger. Thus, the effect of responding-hand alternation on spatial compatibility is greater with frequent alternation as Hommel (1996b) observed for alternation every 8 versus 80 trials (though in his case, only in his last quintiles). Finally, the spatial-compatibility effect increased linearly with each RT quintile as reported by Hommel (1996b).

Again, the significant Field × Hand interaction in RT indicates that spatial compatibility does not suffice to explain the CUD. The evidence for the existence of an IHTT component in SRT remains robust, unaffected by

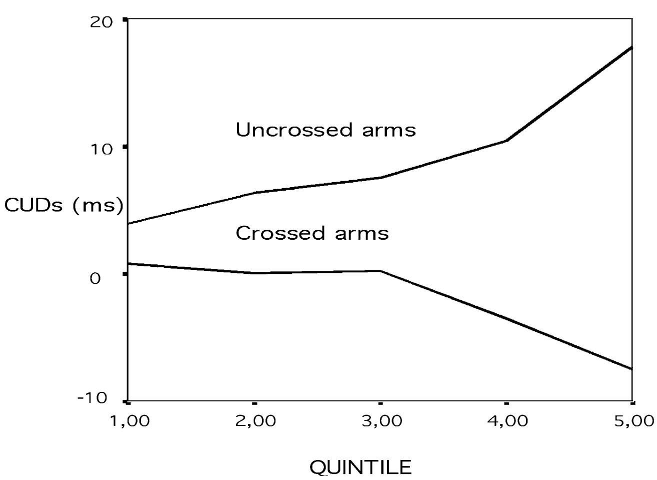

Fig. 2 Simple reaction time differences between crossed and uncrossed hand-field conditions as a function of quintile in Experiment 4

Table 6 Quintile means of RTs (ms) in each combination of Field and Hand and CUDs (ms) as a function of hand Position and Rank of the interval since the last change in the response code (error-free trials only) (N=16)

Position/Rank	Left hand		Right hand		CUD
	Left field	Right field	Left field	Right field	
Uncrossed arms/1	439.66	467.29	451.93	452.84	13.51***
Uncrossed arms/2	425.21	448.80	424.95	433.02	7.76*
Uncrossed arms/3	430.94	442.19	433.06	431.45	6.43*
Crossed arms/1	466.37	443.16	459.69	449.17	−6.35*
Crossed arms/2	435.64	426.56	435.33	418.20	4.02
Crossed arms/3	442.16	422.75	433.61	421.49	−3.64

*p<.05, **p<0.01 (one-tailed tests)

Rank and not modulated by Quintile, as would be expected from a simple relay-time effect.

Experiment 5

Introduction

Experimental effects on CUDs occurring in conditions of periliminal detection (30–35% omission errors) may not necessarily be replicable in supraliminal conditions (0–1% omission errors), and vice versa. It is important therefore to carry out both types of investigation. We therefore repeated Experiment 4 with supraliminal stimuli. Predictions were the same as in Experiment 4.

Subjects

Eight male and eight female experimentally naïve university students (20–28 years of age) were selected and tested using the same inclusion/exclusion criteria and modalities as the previous four studies.

Procedure

This experiment was identical to Experiment 4, except that stimulus distinctiveness was fixed at a stimulus luminance of 1.6 cd/m^2 and a background luminance of 2.9 cd/m^2.

Results

The overall rate of anticipation errors was 0.8% and the overall rate of omission errors was 0.6%.

Reaction times

A 2×2 × 2×3 × 5 repeated measures ANOVA on RTs was carried out. Within factors were Field, Hand, Position, Rank and Quintiles (as Experiment 4). The main effect of RANK was again highly significant ($F_{(adj1.2,17.1)}$=51.3, p<.0001). Mean RTs were 333, 302 and 305 ms as a function of Rank. The effect of Position reached significance this time ($F_{(1,14)}$=11.2, p<.003, one-tailed test), the crossed-hands condition generating longer RTs. Significant interactions involving Field and Hand factors consisted of the Field × Hand interaction ($F_{(1,12)}$=21.3, p<.0001, one-tailed test), the Field × Hand × Position interaction ($F_{(1,12)}$=23.2, p<.0001, one-tailed test) and the Field × Hand × Position × Rank interaction ($F_{(adj1.4,20.8)}$=4.1, p<.022, one-tailed test). The Field × Hand × Rank interaction was clearly not significant ($F_{(\text{adj } 1.6,23.2)}$=0.7, p=.48). As in the previous experiment, and the rest of the SRT literature as well, left-hand contributions to effects involving the Field × Hand interaction were greater than their right-hand counterparts (see Table 8).

In this experiment, the Field × Hand × Quintile interaction fell short of significance, as did all higher order interactions involving Quintile, except the Field × Hand × Position × Quintile interaction ($F_{(\text{adj } 1.6,23.3)}$=15.1, p<.0001, one-tailed test). The nature of this effect was as expected from Hommel (1996b) and was primarily linear (trend analysis: $F_{(1,14)}$=24.9, p<.0001). See Fig. 3.

As in Experiments 2 and 3, we decomposed the *anatomical* component and the *spatial compatibility* component (i.e., pure estimated IHTT costs devoid of the spatial-compatibility effect). See Table 9.

Since this experiment resembles Experiment 4 in all respects except stimulus Luminance, we tested the hypothesis of effects of Luminance on CUDs by implementing Experiments 4 and 5 as split plots in the

Table 7 Decomposition of CUDs as a function of estimated *anatomical compatibility* (adjusted IHTT estimates) and *spatial compatibility* components in reaction times (N=16)

Rank	Anatomical-compatibility component (adjusted IHTT index)	Spatial-compatibility component
Rank 1 (reaction times)	+3.58	+9.93***
Rank 2 (reaction times)	+5.89**	−3.74
Rank 3 (reaction times)	+1.39	−5.03*

*p<.05, **p<.01, ***p<.001 (one-tailed tests)

Table 8 Quintile mean RTs (ms) in each combination of Field and Hand and CUDs (ms) as a function of hand Position and Rank of the interval since the last change in the response code (error-free trials only) (N=16)

Position/Rank	Left hand		Right hand		CUD
	Left field	Right field	Left field	Right field	
Uncrossed/1	321.06	338.06	334.42	330.69	10.36***
Uncrossed/2	292.79	304.31	298.33	301.97	3.94**
Uncrossed/3	296.78	311.03	303.98	304.40	6.92***
Crossed/1	352.49	318.46	345.30	323.70	−6.22*
Crossed/2	312.64	293.26	314.12	295.97	−1.23
Crossed/3	314.79	299.09	317.72	298.91	1.55

*p<.05, **p<.01, ***p<.001 (one-tailed tests)

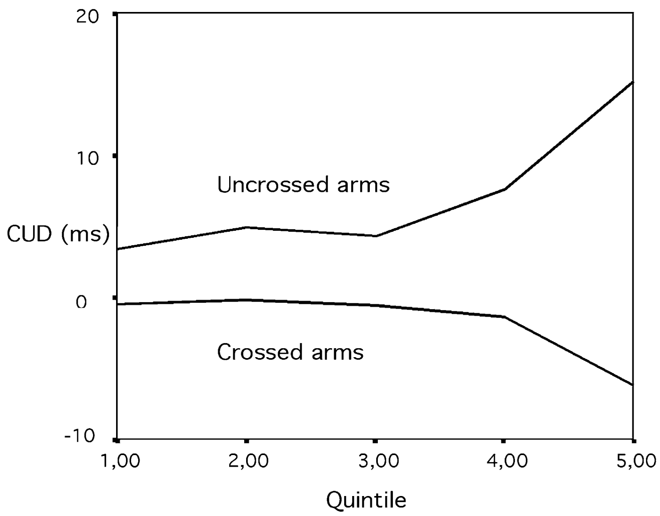

Fig. 3 Simple reaction time differences between crossed and uncrossed hand-field conditions as a function of quintile in Experiment 5

ANOVA. Despite the fact that low target Luminance (higher target/background contrast) very significantly reduced RT from Experiment 4 to 5 (from 439 to 314 ms), all interactions involving Field, Hand and Luminance together fell short of significance (as in Braun et al. 1996).

Discussion

The results of this experiment were similar to all the trends and effects of Experiment 4. A spatial-compatibility effect was definitely confirmed and replicated (via the significant Field × Hand × Position interaction). In addition, longer RTs manifested significantly greater spatial compatibility, as in Hommel (1996b). A significant Field × Hand × Position × Rank interaction confirmed the transient nature of spatial compatibility induced by alternating the responding hand over a small number of trials, but the Field × Hand × Position × Rank × Quintile interaction fell short of significance, which leaves our understanding of the results incomplete.

This experiment again demonstrated presence of a robust IHTT effect (Field × Hand interaction) in SRT, unaffected by Rank and not modulated by Quintile, as would be expected from a simple relay-time effect.

General discussion

The idea according to which the CUD could consist of a spatial-compatibility effect rather than an IHTT effect was explicitly formulated by Broadbent in 1974. However, these are among the very few experiments to have obtained significant spatial-compatibility effects with simple RT since Godbout and colleagues (1995) and Hommel (1996b), who was the first to recognize the phenomenon as such. Just as researchers interested in IHTT have neglected spatial compatibility, those interested in spatial compatibility have neglected IHTT. In fact, what is often called a spatial-compatibility effect or an IHTT effect is usually at least both: when the hands are crossed, the effects are subtractive, and when the hands are not crossed, they are additive. Numerous significant results of this series of experiments illustrate that the spatial-compatibility component of the CUD can be substantial in some simple RT experiments. Hommel (1996b) demonstrated that *frequency* of changes in the response code (specifically shifts in the code from the right to the left or vice versa) significantly favors the spatial-compatibility effect in simple RT. Frequent changes in the response code occurred in most of the conditions of our Experiments 1–5, and we think this is the major reason for our findings of

Table 9 Decomposition of CUDs as a function of estimated *anatomical compatibility* (adjusted IHTT estimates) and *spatial compatibility* components in reaction times (N=16)

Rank	Anatomical-compatibility component (adjusted IHTT index)	Spatial-compatibility component
Rank 1 (reaction times)	+2.07	+8.29***
Rank 2 (reaction times)	+1.35	+2.59*
Rank 3 (reaction times)	+4.23**	+2.68

*p<.05, **p<.01, ***p<.001 (one-tailed tests)

significant spatial compatibility on each occasion it was observed. Whereas the IHTT-estimate component is little affected by the immediacy of the change in response code (RANK effect), the spatial-compatibility-estimate component is far more markedly affected.

Our results further confirm that adding complexity to SRT does not necessarily enhance spatial compatibility, or influence the CUD. *First*, if such were the case, then our Experiment 2 should have yielded very large CUDs, considering that subjects had to reprogram the response code on every trial and that the effort required was very substantial. *Second*, manipulation of stimulus luminance can have tremendous effects on RT, but does not affect CUDs (Brass et al. 2001; Braun and Daigneault 1994; Braun et al. 1996). Furthermore, general RT is only very weakly related to CUDs in simple RT (Braun 1992) and even in complex RT (Braun and Daigneault 1994), viewed meta-analytically. In our three experiments (1, 3 and 4) using periliminal stimuli, spatial-compatibility effects were indeed observed. Our Experiments 4 and 5 were identical except for the use of peri- and supraliminal stimulation, respectively: The spatial- and anatomical-compatibility components of the CUD were not significantly longer in the former than the latter experiment. Yet the effect of our making targets more distinct (by reducing target luminance) on the general RT was huge. Furthermore, the three-press conditions of our periliminal Experiment 1 and supraliminal Experiment 2 yielded CUDs which did not differ significantly, again despite huge differences in general RT. *Third*, our alternating-keys condition of Experiment 1 (involving one press) and our one-press condition of Experiment 2 also yielded CUDs that did not differ significantly, despite huge differences in general RT. However, less credence must be given to the last two arguments because these two experiments differed slightly in other respects than in stimulus luminance. In short, in simple RT, slow and fast RTs (engendered by manipulations of stimulus luminance) do not particularly influence CUDs, nor do they seem to affect spatial compatibility in any significant way. This being said, within the cells of an experiment, sorting the RTs into quintiles did generally replicate Hommel's (1996b) finding to the effect that spatial compatibility is significantly more manifest in the last quintiles (i.e., the longer RTs). This effect reached significance in our Experiments 1, 3, 4 and 5. Furthermore, what is new here is that in these experimental conditions, it was exclusively the spatial-compatibility component, and not the IHTT component, that interacted with RT quintiles. To summarize, these Quintile effects support Hommel's (1996b) statement that certain attentional modulations prolonging RT engender greater interference between the stimulus and response codes when they are spatially incompatible, even in SRT. More precisely, other sources of prolongation of RT (non-spatial manipulation of stimulus and/or response contingencies, reduced target/background contrast) do not enhance spatial-compatibility effects in simple RT: rather, it is truly a specific type of manipulation (e.g., alternation of responding hands or fingers of the same hand) that contributes heavily to engendering spatial-compatibility effects contributing to large CUDs, and in this situation longer RTs are associated with greater differences between spatial compatibility and spatial incompatibility. The only known way to experimentally prolong CUDs significantly in SRT is to introduce preparation of the spatial aspect of the response code. Incidentally, further demonstration of the idea according to which spatial S-R coding is cognitive rather than anatomical, in SRT, would consist of showing that vertical-key alternation also enhances compatibility, an effect that would be all the more credible if it were modulated by Quintile and a fortiori by Rank. Part of such a demonstration has clearly been made for response-choice RT (Hommel 1996a), but not yet for SRT.

Crossing of hand or arm positions is the key manipulation in support of the concept of spatial compatibility. Yet, in simple RT investigations of spatial compatibility, only Anzola et al. (1977) seem to have required the non-responding hand to rest on the body side opposite to the responding hand and they did not observe a spatial-compatibility effect. However, it is really in alternating-hands conditions that this crossing of the hands (or fingers) is likely to have a strong impact, and this particularity had never been implemented in simple RT versions of the Poffenberger paradigm.

Experiments 3, 4 and 5, which all involved a condition with crossed hands, shed special light on spatial compatibility. They suggest that one form of spatial compatibility involves a very dynamic fluctuating attentional mechanism, which is significantly dampened with very brief practice. This is supported by the significant Field × Hand × Position × Rank interaction observed in our Experiment 4 and replicated in Experiment 5. Only Hommel (1996b), as far as we could ascertain, has touched upon this issue in simple RT. In the other simple RT studies, subjects have usually responded with a given finger and a single response key for large blocks of trials (see Iacoboni and Zaidel 1995 for an exception).

There are other lines of evidence to the effect that spatial compatibility occurs in simple RT. With a standard Poffenberger paradigm, Anzola and Vignolo (1992) found that focal brain lesions generally prolonged the CUD. However, patients with parietal lobe lesions presented the longest CUDs of all (mean: 37 ms, versus 13 ms for lesions of the other lobes). In a PET experiment, Marzi et al. (1999) found that in simple RT, when the responding hand and stimulated field were ipsilateral, frontal activation was observed, whereas when they were contralateral, posterior activation was observed. Finally, Iacoboni et al. (1996, 1997) found specific bilateral superior parietal and premotor activation in spatially incompatible RT conditions, which proved distinct from spatially compatible conditions. These were response-choice experiments. A recent event-related fMRI study found activations in the same areas in a SRT implementation of the Poffenberger paradigm (Iacoboni and Zaidel 2003). These studies suggest that the difference between crossed and uncrossed Hand/Field conditions in the Poffenberger paradigm is not only a matter of IHT occurring through the commissures in the crossed conditions. There is probably a lot of processing taking place in the parietal lobes during simple RT that has to do with some sort of S-R spatial map and that influences the CUD. It is still not clear, however, why changes in response code, like key alternation, would be required for those processes to be more evident.

Hommel (1996b) associates spatial compatibility, in simple RT, to interaction between the stimulus and response spatial codes (interference in crossed conditions, facilitation in uncrossed conditions), thus explaining interactions between CUDs and quintiles in his experiments: he reasoned that the longer RTs were most likely to reflect such interactions, and not the shorter RTs. In the current series of experiments, we obtained many significant modulations of the spatial-compatibility component of the CUD by the quintile factor and no modulation of the anatomical component, thus supporting his model.

Computational and flowchart models of SR compatibility are exclusively based on choice-response paradigms. This literature recognizes spatial compatibility as a special case of these paradigms: it is believed to be a more automatic mechanism than other forms, and is termed "anatomical factors" in type 2 and 3 ensembles by Kornblum et al. (1990). It is believed to be carried in "long-term memory", to be "innate", "task-unrelated", "independent of instructions", "long-lasting", "unmodifiable": an "orienting mechanism that drives the oculomotor system" (Tagliabue et al. 2000). However, spatial compatibility has recently been recognized as not so immutable, and far more dynamic, than previously believed. Recent studies have shown that spatial compatibility and also spatial *incompatibility* advantages can be conditioned, in response-choice or go/no go paradigms. Subjects requested to respond only to spatially incompatible targets develop an attentional bias (shorter RTs) towards incompatible targets that persists over time: without intending to do so, the same subjects, several days later, carrying out a task that required randomly mixing compatible and incompatible targets, presented a marked advantage to incompatible stimuli—which is 'of course' an unusual profile and would have been reversed if they had been pre-conditioned to attend to compatible targets (Proctor and Lu 1999; Tagliabue et al. 2000). Even more pertinent to the current findings is the demonstration by Nicoletti and Umiltá (1989) that they could provoke a reliable spatial-compatibility effect in choice RT as a function of horizontal shifts of spatial attention (see also Rubichi et al. 1997 for similar findings). We interpret the current findings, especially those from Experiments 4 and 5, as an extension of this demonstration: it is not the vertical meridian that is critical in separating right and left spatial compatibility, but attention. Attention can be mobilized by cueing vision (as in Nicoletti and Umiltá 1989) or by mobilizing the effector (the current experiments).

We propose that the spatial compatibility observed to date in SRT consists of a form of orienting response. The more the body throws itself to one side, the more it mobilizes a global sensorimotor-orienting response to that side. The adaptive advantage here is obvious: a voluntary movement sideways normally represents an intentional action requiring mobilization of sensory analyzers and motoric attention in everyday life. Usually, this would be triggered by a visual event, and followed by a global action of the body. But the sequence can be reversed, especially considering that the organism is expecting a lateralized target within milliseconds.

Dirnberger et al. (2003) found that a cue to change the responding *finger* (of the same hand) 3 s before a target activated (CNV) more brain areas than a cue without a change of finger, and that these extra brain areas were contralateral, temporoparietal and mid-parietal. However, when a change of responding *hand* was cued, almost the entire contralateral hemisphere was activated. Accordingly, in SRT, when a movement of a single finger is made to induce spatial compatibility, the effect is barely or not significant (Hommel 1996b; our Experiments 1 and 2). But when a new body side is solicited (a change of hands), the effect is highly significant (our Experiments 1, 3, 4, and 5). The orienting response is a global response of the organism involving all the epicritic senses and striate musculature in a single involuntary multimodal sensorimotor reaction. In accordance with the notion that spatial-compatibility effects detected by RT involve an orienting response, Simon (1967) found, in a response choice paradigm, that monaural stimulation of the right or left ear produced a reliable compatibility advantage in RT as a function of the hand used to give the response. The auditory system's bilateral innervation gives all the more credence to interpreting the phenomenon as an orienting response rather than as interhemispheric transfer time.

Broadbent (1974) and Hommel (1996b) have suggested that spatial compatibility might suffice to explain SRT CUDs, thus envisaging that the Poffenberger paradigm be banished from experimental neuropsychology as a way to index interhemispheric relay time. The findings of the present series of experiments firmly establish the Poffenberger paradigm within experimental behavioral neuroscience as a means of indexing interhemispheric relay time. But clearly, there are at least two components to the CUD in SRT (at least, under special response contingency conditions): a spatial-compatibility component and a non-spatial-compatibility component. The latter is probably an anatomical relay-length component (i.e., interhemispheric relay time).

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