Resource limitations in bimanual pointing.

[a] Markus Janczyk, [b] Cosima Schneider, & [c] Constanze Hesse,

[a] Department of Psychology, University of Bremen, Bremen, Germany (ORCID: 0000-0002-9958-3220)
[b] Department of Psychology, University of Tübingen, Tübingen, Germany
[c] School of Psychology, University of Aberdeen, King's College, Aberdeen, Scotland

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Corresponding Author:
Markus Janczyk
University of Bremen
Department of Psychology
Hochschulring 18
28359 Bremen
Germany
Phone: +49 (0)421 218 68720
Email: janczyk@uni-bremen.de

Abstract

Performing coordinated bimanual movements, that is, movements with two hands simultaneously, is a requirement in many activities. At the same time, these movements are subject to temporal and spatial constraints. Here, we focus on the constraints that become observable when pointing movements of different (asymmetric) rather than same (symmetric) amplitudes have to be executed ("spatial interference effect"). The respective performance costs are larger when the stimuli used to indicate the movement targets are symbolic compared with when the endpoints of the movements are cued directly. Previous studies have thus concluded that the source of spatial interference is both 'cognitive' and 'motoric', or more precisely occurs during response selection as well as motor programming. We here asked whether the contribution from motor programming is motoric in the sense as envisaged in dual-task models, that is, whether it can run in parallel to, and interference-free with, other processing stages. In two PRP experiments, Task 1 was bimanual pointing and Task 2 was auditory pitch-discrimination. Based on the effect propagation-logic, the results suggest that the motor programming contribution to bimanual interference also taps into capacity-limited resources and cannot be construed as running in parallel as assumed for the motor stage in dual-task models.

Key words: spatial interference effect; bimanual pointing; PRP; motor programming; effect propagation

Introduction

Many everyday and leisure activities, but also those in working environments, require the orchestrated use of both hands. In experimental research, these actions are referred to as bimanual coordination. Although the superficial impression may be that bimanual coordination is typically done with ease, results from many studies demonstrate constraints concerning the relative timing and the spatial coordination of both hand movements (see Swinnen & Wenderoth, 2004). In the present paper, the focus is on spatial coordination of bimanual pointing movements with different amplitudes.

Spatial interference effect. One often investigated example of such bimanual interference are the longer reaction times (RTs) in bimanual pointing tasks when the amplitudes required for both hands' movements are different (asymmetric) compared to when the amplitudes are the same (symmetric) (Heuer, 1986; see also, e.g., Franz, Zelaznik, & McCabe, 1991). This observation for bimanual movements with asymmetric amplitudes (or, as another example, directions) is referred to as the *spatial interference effect*. There is an ongoing debate about the exact reason for this interference (see, e.g., Blinch et al., 2014; Diedrichsen, Hazeltine, Kennerley, & Ivry, 2001; Hazeltine, Diedrichsen, Kennerley, & Ivry, 2003; Heuer & Klein, 2006; Spijkers, Heuer, Kleinsorge, & van der Loo, 1997; Stanciu, Biehl, & Hesse, 2017), mostly revolving around whether the interference results from processing during response selection or during motor programming (see also Sanders, 1990). Put simply, *response selection* concerns the application of stimulus-response (S-R) mappings, while *motor programming* refers "primarily to the specification of movement parameters" (Spijkers, Heuer, Steglich, & Kleinsorge, 2000, p. 1092; see also Churchland et al., 2012, for work on the neural underpinnings of reaching movements).[1]

[1] Following other authors, Spijkers et al. (2000) further distinguish motor programming from execution which is concerned with efferent commands and the ongoing feedback signals. For our purposes, this further distinction is not relevant though.

Marteniuk, MacKenzie, and Baba (1984) hypothesized that the spatial interference effect is caused by neural cross-talk. According to some authors (e.g., Heuer, 1993; Heuer, Spijkers, Kleinsorge, van der Loo, & Steglich, 1998; Spijkers et al., 1997), a transient coupling occurring during movement programming, that is, when the parameters of both movements are specified, causes the prolonged RTs for asymmetric compared to symmetric movements. In other words, the interference effect and the observable RT difference has a source during motor programming and mainly results from neural crosstalk.

However, in 2001, Diedrichsen and colleagues pointed out that in the earlier, aforementioned studies the movements were specified with symbolic cues, such as words or letters indicating the amplitude of the movements. Conceivably, this requires a sort of translation of stimuli used for cueing the appropriate motor responses. In contrast, if the movement targets were signaled with direct cues, that is, when the endpoints of the movements were used as stimuli and were not to be inferred by the participants from symbolic cues, no spatial interference effect was observed. From these results, the authors suggested that the interference is related to response selection processes rather than motor programming.

Yet, subsequent studies revealed mixed support for this conclusion with some in support of absent bimanual interference when movements are cued directly (e.g., Albert et al., 2007; Diedrichsen, Ivry, Hazeltine, Kennerley, & Cohen, 2003; Hazeltine et al., 2003), while others reported smaller, but still significant interference effects in this case (e.g., Blinch et al., 2014; Blinch, Cameron, Franks, Carpenter, & Chua, 2015; Heuer & Klein, 2006). As a result, it was suggested that the two forms of interference processes might not be mutually exclusive and therefore can occur concurrently (Diedrichsen, Grafton, Albert, Hazeltine, & Ivry, 2006; Heuer & Klein, 2006). Heuer and Klein (2006, p. 242) summarized this as: "Interference between concurrent processes of amplitude specification can be classified as 'motoric', and interference between concurrent processes of cue-response translation can be classified as 'cognitive'."

A distinction between response selection and motor stages has also been made in models of dual-tasking. The most prominent of these models is the response selection bottleneck (RSB) model of Pashler (1994; see also Welford, 1952). The important characteristic distinguishing both stages – we will introduce the model in more detail in the next section – is that only response selection requires a central capacity, while processes subsumed under the motor stage can run in parallel with all other processes without causing interference.

The main purpose of the present study is to investigate whether the contribution of motor programming to the spatial interference effect is 'motoric' also in the sense of the motor stage of dual-task models, that is, whether it can run in parallel to and interference-free with other processes or not. To this end, we employed the effect propagation-logic, which can be used within psychological refractory period (PRP) experiments.

PRP experiments and effect propagation. Each trial in a PRP experiment consists of two different tasks. The two stimuli (S1 and S2) are presented consecutively with a varying stimulus onset asynchrony (SOA), and require separate responses (R1 and R2). A typical result is that SOA has little influence on the RTs in Task 1 (RT1), but those in Task 2 (RT2) increase when SOA decreases. This increase in RT2 is called the *PRP effect* (Telford, 1931), and is often accounted for by the RSB model (Pashler, 1984, 1994; Welford, 1952).

According to the RSB model, processing of a task is divided into three stages, namely (i) a perceptual stage, (ii) a central stage of response selection, and (iii) a motor stage (see Fig. 1). The critical assumption is that only the pre- and post-central (i.e., perceptual and motor) stages can run in parallel with other stages. In contrast, this is not possible for the response selection stage and, hence, only one such stage can be processed at any time. Thus, this stage is conceived as capacity-limited and constituting a (structural) bottleneck. In trials with a short SOA, the central stage of Task 2 is postponed until the central stage of Task 1 has finished and the bottleneck has been released from Task 1. This waiting time is called *cognitive slack*.

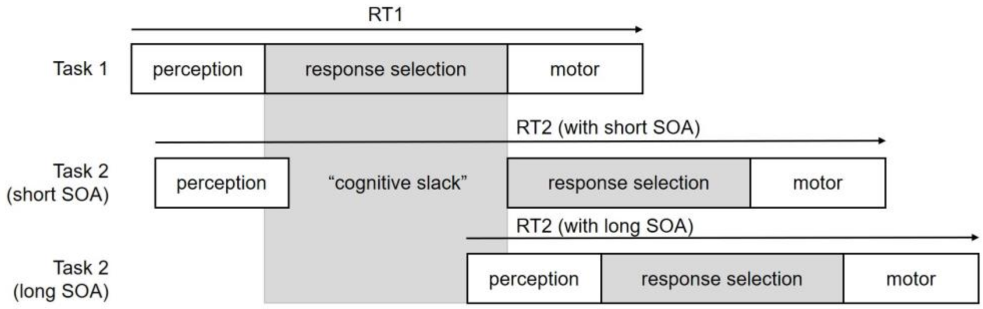

Figure 1. Illustration of the response selection bottleneck (Pashler, 1994). (RT1 and RT2 refer to the response times in Task 1 and 2, respectively).

This model makes several predictions concerning the effects of manipulating these stages in either task on both RT1 and RT2. Most important for our purposes are manipulations implemented in Task 1 (referred to as Principles 1 and 2 by Pashler, 1994). First, if a manipulation prolongs any stage up to and including the response selection stage of Task 1, the onset of Task 2 response selection is delayed by the same amount and thus the effect observed in RT1 should become visible to the same degree in RT2 – at least with short SOAs. With long SOAs, Task 2 response selection often starts sufficiently late to not be affected by the delayed release of the bottleneck from Task 1. Second, if, in contrast, the Task 1 manipulation lengthens the motor stage of Task 1, the resultant effect should only become visible in RT1. This is the case, because the motor stage is, as mentioned above, assumed to run in parallel to and interference-free with other stages and releasing the bottleneck is therefore unaffected by this manipulation.

Combining these two principles has sometimes been termed the *effect propagation-logic* which can be used to distinguish a post-central motor origin of an effect from an earlier one, that is, one during response selection (see Durst & Janczyk, 2018; Janczyk, Humphreys, & Sui, 2019; Miller & Reynolds, 2003). In the present study, we use these ideas to assess whether response programming in a bimanual pointing task falls into the motor stage or is better subsumed under the central and capacity-limited stage often associated with response selection.

Experiments and hypotheses. We report two experiments using the effect propagation-logic to investigate the nature of the motor programming and response selection contributions to the spatial interference effect in bimanual pointing in more detail. Bimanual pointing was always Task 1 in our PRP experiments and binary tone-discrimination with vocal responses was the (unrelated) Task 2. In Experiment 1, we used the letters “L” and “K” as symbolic cues for Task 1, while in Experiment 2 we employed arrows as the Task 1 cueing stimuli (see also Stanciu et al., 2017).

Predictions for the situation with a short SOA are illustrated in Figure 2. To begin with, it seems uncontroversial that parts of the spatial interference effect with symbolic cues results from the capacity-limited stage of response selection. Thus, in no case would we predict that the effect observed in RT1 is entirely absent in RT2 (as it would be if all of the spatial interference effect results from parallel and interference-free motor processing).

At first glance, classifying amplitude specification as “motoric” (Heuer & Klein, 2006) lends some credibility to subsuming this process under the motor stage in models like the RSB model (Pashler, 1994). This situation is illustrated in Figure 2a. In this case, only the additional time (required for performing asymmetric amplitudes) resulting from the response selection contribution postpones release of the bottleneck by Task 1. Thus, only this part propagates into RT2 and, as a consequence, the RT2 difference between symmetric and asymmetric amplitudes is smaller than the RT1 difference.

In contrast, under the assumption that motor programming requires the same resources as response selection does, the contribution of motor programming to the spatial interference effect also delays release of the bottleneck from Task 1. This situation is illustrated in Figure 2b. In this case, the effect observed in RT2 should be of the same size as the one observed in RT1.

For the long SOA, both scenarios make the same predictions: First, RT2 is much shorter than at the short SOA (i.e., the PRP effect) and, second, the propagation of the RT1 effect into

RT2 is smaller than at the short SOA or even absent. In other words, ideally, an overadditive interaction of SOA and the symmetric vs. asymmetric amplitudes manipulation is expected, that is, the effect of symmetry should be larger with the short SOA than with the long SOA.

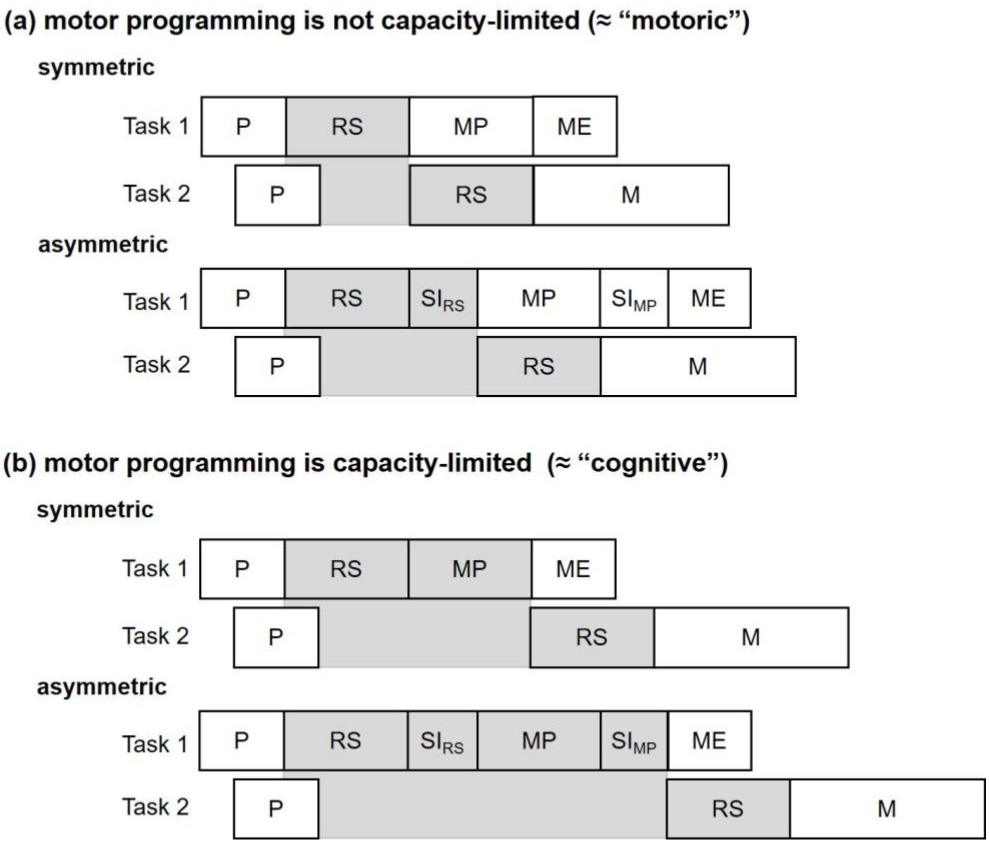

Figure 2. Predictions derived for the present study for the situation with a short SOA. In the upper panel (a) it is assumed that motor programming (MP) is motoric in the sense of dual-task models in that it can run in parallel to and interference-free with all other processing stages. In the lower panel (b), in contrast, it is assumed that motor programming implicates the use of limited resources, and thus is subsumed under the bottleneck as well. (P = perception, RS = response selection, ME = motor execution, SI_{RS} = spatial interference resulting from response selection, SI_{MP} = spatial interference resulting motor programming, M = motor stage [any further subdivision of this stage is theoretically irrelevant as far as Task 2 is concerned; the size of the boxes have an arbitrary length and are merely meant for illustration here)

Experiment 1

Method

Participants. Forty-eight native speakers of German (35 female; mean age = 23.3 years) participated in this experiment. They were recruited from the participant pool at the University of Tübingen (Germany), were naïve regarding the hypotheses of this experiment, and signed informed consent prior to data collection. Participants received 8 € or course credit for their participation.

Apparatus and stimuli. Stimulus presentation and response collection were controlled by a standard PC connected to a 17-inch monitor. The two letters “L” or “K” (for the German words “lang” [long] and “kurz” [“short”]) were presented in white color in the center of an otherwise black screen and served as S1. A low- or high-pitched tone (300 vs. 900 Hz) was presented via headphones as S2.

Task 1 responses (R1) were given via manual keypresses of both hands. Task 2 responses (R2) were the two vocal utterances “tipp” and “topp”. In total, there were six manual response keys, aligned in two rows of three keys from the participant towards the monitor (see Figure 3). The keys were operated by the left and right index fingers of the participants. The two keys closest to the participant served as home-keys. A microphone (to register the vocal R2) was placed in between the home-keys and a voice key was used to measure RT2.

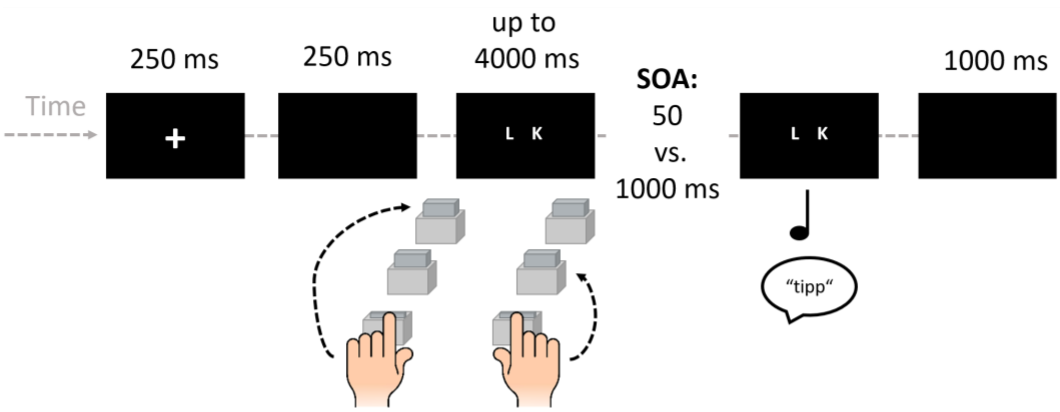

Figure 3. Trial structure and tasks in Experiment 1. In each trial, participants first responded to both letters by moving each index finger to the respective target key. After a variable SOA of 50 vs. 1000 ms, a low vs. high tone was presented and required a vocal response (“tipp” vs. “topp”). The two response keys closest to the participants were the home-keys from which the movements started.

Task and procedure. The trial structure is illustrated in Figure 3. Each trial started when participants pressed and held down both home-keys (see Fig. 3). Then, a fixation cross was presented (250 ms), followed by a blank screen (250 ms). After that, S1 was presented until both R1 and R2 were registered (or for a maximum of 4000 ms). S2 was played after an SOA of 50 or 1000 ms. The next trial started after an inter-trial interval (ITI) of 1000 ms. In case of errors, specific error feedback (incorrect responses in either task, wrong response order, unclear speech production in Task 2, too slow responding) was provided for 1000 ms before the ITI.

The two S1 letters indicated the two targets to which participants should move their index fingers. There were four types of combinations possible: “KK”: short amplitude for both hands, “LL”: long amplitude for both hands, ”KL”: left-hand short, right-hand long amplitude, and “LK”: left-hand long and right-hand short amplitude (“K” abbreviates “kurz”, German for “short”; “L” abbreviates “lang”, German for “long”). Trials with different required amplitudes were considered asymmetric, and those requiring the same amplitudes were considered symmetric.

Participants first performed a short familiarization block of 20 randomly drawn trials, followed by one practice and eight experimental blocks of 48 trials each, resulting from three repetitions of all combinations of 4 S1 × 2 S2 × 2 SOAs. All trials within a block were presented in random order. Participants received written instructions that emphasized speed and accuracy, and were asked to give R1 and R2 successively in fixed order. The S2-R2 mapping was counterbalanced across participants.

Design and analyses. Movement onset was measured separately for both hands, from S1 onset until participants left the respective home-key. RT1 were calculated as the mean of the movement onsets of the left and right hand, and movement times (MTs) were measured from then on until the target button was pressed. RT2 were measured from S2 onset until the vocal R2 was registered. Data from the familiarization and practice block were not analyzed as were trials in which the movement onset of both hands differed by more than 100 ms. Further, trials with task-unspecific errors (missing responses, wrong response order, etc.) were excluded from data analyses (2.85% of all trials). For the analysis of RTs, trials deviating more than 2.5

standard deviations from the individual cell mean were considered as outliers and excluded from analysis.

The predictions will be, as is common in the field of PRP research and related studies, tested using Analyses of Variance (ANOVA). Thus, mean correct RTs and error rates (ERs) were submitted to separate 2 × 2 repeated-measures ANOVAs with the within-subject factors (1) symmetry (symmetric vs. asymmetric) and (2) SOA (50 ms vs. 1000 ms). For completeness, significant interactions are followed up with paired-samples *t* tests. The most critical comparison to distinguish the two scenarios elaborated on in the introduction (see also Fig. 2) is the comparison of the RT1 effect and the RT2 effect at the short SOA, which can be conceived as a planned comparison. This comparison was addressed with a paired-samples *t* test. Descriptive results on MTs are reported for completeness, but were not further analyzed as we had no clear predictions for this measure. Effect sizes are reported as η_p^2 for ANOVAs and as Cohen's d_z for *t* tests.

Results

Mean RT1s and RT2s are illustrated in Figure 4 (left panel; see also Table 1), and mean ERs are summarized in Table 1. For RT analyses, 2.07 % and 2.51 % of all trials were excluded as outliers in Task 1 and 2, respectively.

Task 1. RT1s were on average 28 ms shorter for symmetric (384 ms) than for asymmetric trials (412 ms), $F(1,47) = 31.04$, $p < .001$, $\eta_p^2 = .40$. They were not affected by the SOA, $F(1,47) = 1.74$, $p = .194$, $\eta_p^2 = .04$, and the interaction between SOA and congruency was also not significant, $F(1,47) = 0.61$, $p = .439$, $\eta_p^2 = .01$.

Fewer errors were made in symmetric (0.37 %) relative to asymmetric trials (6.99 %), $F(1,47) = 40.54$, $p < .001$, $\eta_p^2 = .46$. The main effect of SOA was not significant, $F(1,47) = 0.10$, $p = .753$, $\eta_p^2 < .01$, and neither was the interaction, $F(1,47) = 0.16$, $p = .689$, $\eta_p^2 < .01$.

Task 2. RT2s were on average 396 ms longer at the 50 ms (1274 ms) as compared to the 1000 ms SOA (878 ms), $F(1,47) = 271.92$, $p < .001$, $\eta_p^2 = .85$. The main effect of symmetry was also significant, with on average 110 ms shorter RT2s in symmetric (1021 ms) than in asymmetric trials (1131 ms), $F(1,47) = 142.81$, $p < .001$, $\eta_p^2 = .75$. The (overadditive) interaction between SOA and symmetry was significant, $F(1,47) = 173.19$, $p < .001$, $\eta_p^2 = .79$. The symmetry effect of 189 ms at the 50 ms SOA was significant, $t(47) = 13.36$, $p < .001$, $d = 1.93$, as was the 31 ms symmetry effect at the 1000 ms SOA, $t(47) = 4.80$, $p < .001$, $d = 0.69$. Considering only the short 50 ms SOA, the effect of symmetry was larger for Task 2 than for Task 1, $t(47) = 12.54$, $p < .001$, $d = 1.81$.

ERs varied between 2.32 % to 3.33 % and were not affected by our experimental variations, SOA: $F(1,47) = 3.31$, $p = .075$, $\eta_p^2 = .06$; symmetry: $F(1,47) = 3.15$, $p = .083$, $\eta_p^2 = .07$; interaction: $F(1,47) = 0.99$, $p = .325$, $\eta_p^2 = .02$.

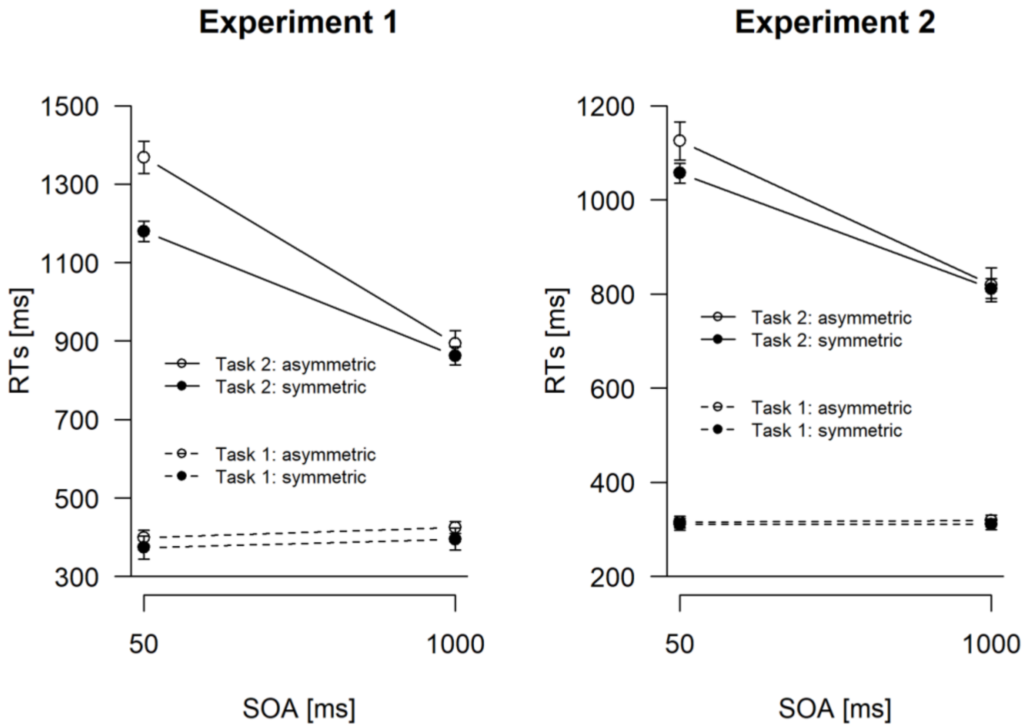

Figure 4. Mean reaction times (RTs) in milliseconds (ms) for Task 1 and 2 as a function of stimulus onset asynchrony (SOA; 50 vs. 1000 ms) and symmetry (asymmetric vs. symmetric) in Experiment 1 (left panel) and Experiment 2 (right panel). Note that the y-axes have different scales due to the general difference in RT-levels between both experiments. Error bars are between-subject standard errors of each mean RT. Within-subject standard errors are provided in Table 1 for Experiment 1 and in Table 3 for Experiment 2.

Table 1. Mean reaction times (RTs) in milliseconds (ms) and Error Rates (in %) for Task 1 and Task 2 in Experiment 1 as a function of stimulus onset asynchrony (SOA) and symmetry. Values in parentheses are within-subject standard errors (Morey, 2008).

		Task 1		**Task 2**	
Symmetry	**SOA [ms]**	RT [ms]	Error Rate [%]	RT [ms]	Error Rate [%]
Asymmetric	50	399 (9)	7.18 (0.9)	1368 (19)	3.33 (0.3)
Symmetric	50	374 (13)	0.35 (0.6)	1179 (13)	2.56 (0.3)
Asymmetric	1000	425 (11)	6.79 (0.8)	894 (13)	2.48 (0.3)
Symmetric	1000	395 (11)	0.38 (0.6)	863 (15)	2.32 (0.3)

Exploratory Analyses: MTs and inter-response Interval. Mean MTs for the left hand, right hand, and averaged across both hands as a function of S1 stimulus and SOA are provided in Table 2. While SOA seemed to have no clear effect on mean MTs, the type of stimulus had. Descriptively, MTs were shortest with two short (symmetric) amplitudes, intermediate with two long (symmetric) amplitudes, and longest for the asymmetric conditions with one short and one long amplitude. The following analyses are based on data where outliers in both tasks were excluded (for outlier definition/criteria, please see the Section Design and analyses). Regarding the inter-response interval (IRI), R2 (vocal responses) were given after the longer of the two Task 1 movements was finished in 97.7 % of all trials. For these trials, the mean IRI was 406 ms in asymmetric trials and 383 ms in symmetric trials with the short SOA of 50 ms.

Table 2. Movement times (in ms) for Task 1 in Experiment 1 as a function of the Task 1 stimulus (S1) and stimulus onset asynchrony (SOA). Values in parentheses are within-subject standard errors. (Note: S = short, L = long)

Symmetry	**S1: left/right hand**	**SOA**	Movement times [ms]		
			left hand	right hand	mean
Asymmetric	S/L	50	584 (13)	613 (13)	599 (13)
	L/S	50	618 (12)	632 (12)	625 (12)
Symmetric	S/S	50	418 (14)	429 (14)	424 (14)
	L/L	50	521 (13)	529 (13)	525 (13)
Asymmetric	S/L	1000	586 (11)	619 (9)	603 (10)
	L/S	1000	622 (12)	632 (13)	627 (12)
Symmetric	S/S	1000	441 (15)	452 (15)	446 (14)
	L/L	1000	553 (15)	561 (15)	557 (15)

Discussion

As expected, we observed longer RT1s for asymmetric than for symmetric trials, reflecting the spatial interference effect in bimanual pointing. For Task 2, we observed a PRP effect, that is, longer RT2s for the short than for the long SOA. The most interesting result relates to the size of the spatial interference effect at the short SOA when comparing RT1s and RT2s. The observed effect in the unrelated Task 2 was even *larger* than the effect in Task 1.

While this outcome was not predicted under both scenarios discussed in the introduction, it is certainly incompatible with the idea that motor programming is ‘motoric’ in the sense of the motor stage in the RSB model (Pashler, 1994), as in this case, the effect should have become smaller in RT2.

Before drawing further conclusions, we aimed to replicate the results of Experiment 1 with different cueing stimuli in Task 1. Instead of using letters we now used arrows as cueing stimuli. The same arrows have been used in a study by Stanciu et al. (2017; see their low S-R compatible condition in Exp. 1). Despite increased S-R compatibility, a reliable spatial interference effect was observed with these stimuli.

Experiment 2

Method

Participants. Forty-eight native speakers of German (43 female; mean age = 23.4 years) participated in this experiment. They were recruited from the participant pool at the University of Tübingen (Germany), were naïve regarding the hypotheses of this experiment, and signed informed consent prior to data collection. Participants received 8 € or course credit for their participation.

Apparatus, stimuli, task, procedure, design, and analyses. In most aspects, this experiment resembled Experiment 1. The only change relates to the cueing stimuli (S1) used for the bimanual pointing task. In Experiment 2, two white arrows (pointing upwards or downwards) presented in the center of an otherwise black screen served as S1. The two arrows indicated the two targets to which participants should move their index fingers. There were four types of combinations possible: both arrows pointing downwards (short amplitude for both hands), both arrows pointing upwards (long amplitude for both hands), left arrow pointing downwards and right arrow pointing upwards (left hand short, right hand long amplitude), and left arrow pointing upwards and right arrow pointing downwards (left hand long, right hand short amplitude). 1.84 % of the trials were excluded for unspecific errors (see Exp. 1 for more details).

Results

Mean RT1s and RT2s are shown in Figure 4 (right panel; see also Table 3). Mean ER for Task 1 and Task 2 are summarized in Table 3. For RT analysis, 2.22 % and 2.86 % of all trials were excluded as outliers in Task 1 and 2, respectively (using the same criteria as in Experiment 1).

Task 1. RT1s were on average 7 ms shorter in symmetric (311 ms) relative to asymmetric trials (318 ms), $F(1,47) = 13.92$, $p = .001$, $\eta_p^2 = .23$, but were not significantly different for both SOAs, $F(1,47) = 2.91$, $p = .095$, $\eta_p^2 = .06$. However, the interaction between SOA and symmetry was significant, $F(1,47) = 4.66$, $p = .036$, $\eta_p^2 = .09$. Post-hoc analysis confirmed that the 5 ms symmetry effect was significant for the 50 ms SOA, $t(47) = 2.39$, $p = .021$, $d = 0.35$, as was the 9 ms symmetry effect for the 1000 ms SOA, $t(47) = 4.12$, $p < .001$, $d = 0.59$.

ERs varied between 0.33 % to 1.06 % and were unaffected by the experimental variations, SOA: $F(1,47) = 0.42$, $p = .523$, $\eta_p^2 = .01$; symmetry: $F(1,47) = 3.44$, $p = .070$, $\eta_p^2 = .07$; interaction: $F(1,47) = 0.14$, $p = .710$, $\eta_p^2 < .01$.

Task 2. RT2s were 276 ms longer at the 50 ms SOA (1091 ms) than at the 1000 ms SOA (815 ms), $F(1,47) = 133.09$, $p < .001$, $\eta_p^2 = .74$, and they were 38 ms shorter in symmetric (934 ms) than in asymmetric trials (972 ms), $F(1,47) = 49.77$, $p < .001$, $\eta_p^2 = .51$. The (overadditive) interaction between SOA and symmetry was also significant, $F(1,47) = 47.25$, $p < .001$, $\eta_p^2 = .50$: The symmetry effect was 68 ms for the 50 ms SOA, $t(47) = 7.45$, $p < .001$, $d = 1.08$, and was reduced to 8 ms at the 1000 ms SOA, $t(47) = 2.18$, $p = .034$, $d = 0.31$. Considering only the 50 ms SOA, the effect of symmetry was again larger for Task 2 than for Task 1, $t(47) = 7.25$, $p < .001$, $d = 1.05$, replicating our results from Experiment 1.

Fewer errors were made at the short SOA (1.93 %) relative to the long SOA (2.49 %), $F(1,47) = 5.64$, $p = .022$, $\eta_p^2 = .11$. Neither the main effect of symmetry, $F(1,47) = 0.47$, $p = .495$, $\eta_p^2 = .01$, nor the interaction effect were significant, $F(1,47) = 0.03$, $p = .865$, $\eta_p^2 < .01$.

Table 3. Mean reaction times (RTs) in milliseconds (ms) and Error Rates (in %) for Task 1 and Task 2 in Experiment 2 as a function of stimulus onset asynchrony (SOA) and symmetry. Values in parentheses are within-subject standard errors (Morey, 2008).

		Task 1		**Task 2**	
Symmetry	**SOA [ms]**	RT [ms]	Error Rate [%]	RT [ms]	Error Rate [%]
Asymmetric	50	316 (1)	1.06 (0.4)	1125 (17)	1.89 (0.2)
Symmetric	50	311 (1)	0.49 (0.2)	1057 (12)	1.97 (0.2)
Asymmetric	1000	319 (1)	0.73 (0.3)	819 (14)	2.41 (0.2)
Symmetric	1000	311 (1)	0.33 (0.3)	812 (14)	2.56 (0.2)

Exploratory Analyses: MTs and inter-response Interval. Mean MTs for the left hand, right hand, and averaged across both hands as a function of S1 stimulus and SOA are provided in Table 4. Similar to Experiment 1, SOA had no clear effect on mean MTs, while the type of stimulus had. Again, MTs were shortest when both hands moved short (symmetric) amplitudes, intermediate for two long (symmetric) amplitudes, and longest for the asymmetric conditions with one short and one long amplitude. Regarding the IRI, R2 was given after the longer of the two Task 1 movements was finished in 98.4% of all trials. For these trials, the mean IRI was 339 ms in asymmetric trials and 345 ms in symmetric trials with the short SOA of 50 ms.

Table 4. Movement times (in ms) for Task 1 in Experiment 2 as a function of the Task 1 stimulus (S1) and stimulus onset asynchrony (SOA). Values in parentheses are within-subject standard errors. (Note: S = short, L = long)

Symmetry	**S1: left/right hand**	**SOA**	Movement times [ms]		
			right hand	right hand	mean
Asymmetric	S/L	50	507 (7)	525 (7)	516 (7)
	L/S	50	524 (7)	528 (8)	526 (7)
Symmetric	S/S	50	404 (8)	411 (8)	408 (8)
	L/L	50	489 (7)	493 (7)	491 (7)
Asymmetric	S/L	1000	512 (6)	529 (6)	520 (6)
	L/S	1000	525 (6)	527 (7)	526 (6)
Symmetric	S/S	1000	406 (10)	408 (10)	407 (10)
	L/L	1000	504 (7)	506 (7)	505 (7)

Discussion

The results, by and large, replicate those obtained in Experiment 1. The spatial interference effect was observed in Task 1, albeit it was of much smaller size than in Experiment 1. At the same time, the size of the spatial interference effect at the short SOA was again larger in (the unrelated) Task 2 compared to Task 1.

General Discussion

Performing bimanual pointing movements is subject to several constraints concerning the relative timing and the spatial coordination of both hands. One example, we refer to as the spatial interference effect, is that RTs are often increased when both hands' movements require asymmetric (different) rather than symmetric (same) amplitudes (Heuer, 1986), at least when the movements are cued symbolically. With direct cues, in contrast, this effect is smaller and sometimes even absent (e.g., Diedrichsen et al., 2006; Heuer & Klein, 2006).

These results were taken to suggest that response selection contributes to the spatial interference effect to a large(r) part, but that motor programming, that is, the specification of movement parameters, has an additional contribution. These two contributions have been termed 'cognitive' and 'motoric' (Heuer & Klein, 2006), respectively. Response selection and motor stages are also distinguished in models of dual-tasking, such as the RSB model (e.g., Pashler, 1994). An important aspect in these conceptualizations is that response selection is subject to capacity-limitations, while this is not true for processes subsumed under the motor stage. We here asked whether motor programming can also be considered ‘motoric’ in the sense of dual-task models.

In our two PRP experiments, bimanual pointing with symbolic cues was Task 1 and an auditory pitch-discrimination was Task 2. In Experiment 1, we used letters as cues and in Experiment 2 we used arrows (similar to the low S-R compatibility condition used by Stanciu et al., 2017). The spatial interference effect was observed in Task 1 RTs, but it was much smaller in Experiment 2 than in Experiment 1. Taking advantage of the effect propagation-logic (e.g., Miller & Reynolds, 2003), two predictions can be derived for Task 2 RTs at the short SOA (see also Fig. 2). First, if the motor programming contribution requires central capacity in the same way as response selection does, the same RT1-difference (as observed between symmetric and asymmetric movements) should be observed in RT2. Second, if motor programming is subsumed under the motor stage of the RSB model, the effect in RT2 should be smaller than the one in RT1.

In both experiments, the effect was even larger in RT2 than in RT1 (i.e., it did not simply propagate, but actually *over*propagated), a prediction that was not made by any of the two scenarios. However, this result is certainly not compatible with the view that motor programming is running in parallel and interference-free, as envisaged by the motor stage in the RSB model. Rather, motor programming appears to require the same central resource as response selection does. The RSB model can also not account for the overpropagation. While similar observations have been made in other studies as well (Logan & Gordon, 2001; Hommel, 1998; Janczyk, 2016, Exp. 1/2; Janczyk, Renas, & Durst, 2018; Wirth, Pfister, Janczyk, & Kunde, 2015; but see also Ellenbogen & Meiran, 2011; Schubert, Fischer, & Stelzel, 2008), the reasons are, however, not well understood yet (see also Koob, Ulrich, & Janczyk, 2021, for a discussion). As one possible explanation, Janczyk et al. (2018) suggested response monitoring as a contributing factor to overpropagation (Welford, 1952; see also Jentzsch, Leuthold, & Ulrich, 2007; Wirth, Janczyk, & Kunde, 2018), and the same might have occurred in the present experiments as well. As suggested by a reviewer, an additional contribution to this overpropagation might come from interference occurring during movement execution in Task 1 (see McLeod, 1980, for a critical methodological discussion of measuring capacity requirements during movement execution). The exploratory analyses on MTs show that R2 was mostly given after the Task 1 movements were finished. At the most relevant short SOA, however, the IRI (i.e., the time between finishing R1 and providing R2) was longer for asymmetric trials in Experiment 1, but descriptively slightly shorter for asymmetric trials in Experiment 2. Thus, this suggests that there was no consistent additional contribution of interference resulting from movement execution. In addition, an empirical argument against this suggestion can be made. While it seems uncontroversial that processes of movement planning interfere with grasping movements (e.g., Janczyk, Franz, & Kunde, 2010; Janczyk & Kunde, 2010), findings on interference from movement execution are less consistent (e.g., Liu, Chua, & Enns, 2008; see also Lee & Hsieh, 2009; vs. Hesse & Deubel, 2011; Hesse, Schenk & Deubel, 2012). Thus, at present, we would argue that the observed overpropagation cannot be attributed solely to interference from movement execution although there may be some (small) additional effect in our study.

In sum, it appears as if those processes contributing to the spatial interference effect require a limited central capacity, commonly related to response selection, and are thus subject to interference from other ongoing tasks. This interpretation fits well with the recent proposal that the spatial interference effect does not depend so much on the type of cueing (symbolic vs. direct), but rather on the cognitive demands the task poses on the actor (Stanciu et al., 2017). Stanciu and colleagues used a direct cueing condition alone or with a secondary task (an attention task in Exp. 1 and a working memory task in Exp. 2). Without an additional task, no spatial interference effect was observed, but an interference effect was present when an additional resource demanding task had to be performed. This conclusion was further supported in a recent study (Hesse, Koroknai, & Billino, 2020) comparing the performance of participants that varied in their available cognitive and/or motor capacity (i.e., older adults, younger adults, and younger musicians). Specifically, it was observed that the spatial interference effect increased as both processing speed and capacity decreased. Another interesting observation in our present data, which further supports this argument, is the reduced size of the spatial interference effect in Experiment 2 (7 ms) as compared to Experiment 1 (28 ms). That both, overall RTs and spatial interference effects decrease as S-R compatibility between cues and required actions increase, nicely aligns with the observations by Stanciu et al. (2017) and is compatible with the notion that overall task difficulty, and hence the amount of processing capacity required, is an important factor for the size of interference effects.

Attributing the emergence of spatial interference to a capacity-limited processing stage, and to response selection in particular, suggests a link to ideomotor theory. Briefly, this theory assumes that bodily movements are selected via an anticipation of their resulting sensory states, their action effects (see Harleß, 1861, and Pfister & Janczyk, 2012, for a translation; for reviews, see Badets, Koch, & Philipp, 2016; Shin, Proctor, & Capaldi, 2010). The most compelling evidence for this comes from studies on response-effect compatibility: In the spatial domain this means, that, for example, a left response is given faster when it predictably has a left action effect than when the effect is right-sided (Kunde, 2001; see also Janczyk, Durst, & Ulrich, 2017; Janczyk & Lerche, 2019; Koch & Kunde, 2002; Pfister & Kunde, 2013; and many others). Paelecke and Kunde (2007) have localized the process of effect anticipation within the capacity-limited stage as well (see their Exp. 1-3). However, when bodily movements were first associated with action effects and these action effects were then used as stimuli, the requirement of the limited capacity was considerably reduced (see their Exp. 4-5). Janczyk and Kunde (2020) went a step beyond and even suggested that the capacity-limited stage in dual-task models may be better described as comprising effect anticipation rather than response selection. In other words, dual-task problems arise (at least in parts), because the cognitive system cannot create and/or maintain multiple effect representations by itself at the same time. Concerning bimanual pointing movements, using direct cues, and perhaps even – more or less – S-R compatible arrows as in our Experiment 2, may be interpreted in a way that the effects of the movements (i.e., the final states of the fingers) are presented as stimuli. This in turn should then reduce the requirement of the limited capacity and lead to a small(er) spatial interference effect. In fact, action effects have also been shown to affect and determine the efficacy of bimanual movements. As one example, the RT advantage of homologous over non-homologous finger presses can be reversed if the latter lead to similar and the former to dissimilar action effects (Janczyk, Skirde, Weigelt, & Kunde, 2009; see also Janczyk & Kunde, 2014; Kunde, Krauss, & Weigelt, 2009; Kunde & Weigelt, 2005; Mechsner, Kerzel, Knoblich, & Prinz, 2001).

One objection to the present study and its rationale is the perhaps overly simplifying distinction between cognitive and motor processes. Yet, the RSB model underlying our rationale and the derived predictions assumes this clear distinction and we based our hypotheses on this theory and distinction in the present context. In the context of ideomotor theory, some studies reported an influence of action effects on action execution (e.g., Hommel, Lippelt, Gurbuz, & Pfister, 2017; Shin & Proctor, 2012; but see Schonard, Xiong, Proctor, & Janczyk, 2021, for a critical view on this), thereby weakening the clear distinction. In addition, it has been shown that models that do not assume entirely serial stages (such as cascade models) can mimic predictions from purely serial models (Miller, van der Ham, & Sanders, 1995).

In sum, the present study contributes to our knowledge concerning bimanual coordination. In particular, the result attribute the sources for spatial interference in bimanual pointing tasks to a capacity-limited stage of processing, rather than subsuming motor programming under the motor stage in dual-task models.

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