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Psychological Research
An International Journal of Perception, Attention, Memory, and Action

ISSN 0340-0727
Volume 79
Number 4

Psychological Research (2015)
79:658-668
DOI 10.1007/s00426-014-0601-5


Psychological Research
An International Journal of Perception, Attention, Memory, and Action
Volume 79 Number 4 July 2015

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DOI 10.1007/s00426-014-0601-5

ORIGINAL ARTICLE

Constrained postures and spatial S–R compatibility as measured by the Simon effect

Magali Kreutzfeldt · Marco Leisten · Jochen Müsseler

Received: 24 October 2013 / Accepted: 19 July 2014 / Published online: 20 August 2014

Abstract Whereas working under constrained postures is known to influence the worker's perceived comfort and health, little is known in regard to its influence on performance. Employing an Auditory Simon task while varying posture, we investigated the relationship between constrained postures and cognitive processes in three experiments. In Experiment 1 and 2, participants operated a rocker switch or a control knob with one hand either in front or in the back of their body and while either sitting or kneeling. Perceived musculoskeletal exertion was gathered with a questionnaire. Results of the first two experiments showed differently perceived comfort and a minor effect of constrained posture on cognitive performance. However, results indicated that spatial coding in the back compares to either a virtual turn of the observer towards the control device (front-device coding) or along the observer's hand (effector coding). To clarify this issue the rocker switch was operated with one or two hands in Experiment 3, showing a comparable coding only in the one-hand condition and indicating evidence for the effector-coding hypothesis in the back.

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Introduction

It is well accepted that cognitive manipulations (e.g., amount of sensory information modulating attentional load, sleep deprivation) affect body posture (e.g., Fabbri, Martoni, Esposito, Brighetti, & Natale, 2006; Teasdale, Bard, LaRue, & Fleury, 1993). In contrast, little is known about an effect in the opposite direction. In the present paper we face the question whether the postures of our body exert an influence on cognitive processing.

The relevance of this question comes into consideration when looking at a study conducted by the German Federal Institute for Vocational Education and Training and the Federal Institute for Occupational Safety and Health in 2006 (as cited in BMAS & BAuA, 2009; see also Beermann, Brenscheidt, & Siefer, 2005). As one outcome of this employee poll, 14.3 % of 20,000 interviewed employees stated they had to work in constrained postures on a frequent basis and 50.8 % of them felt strained by this. Constrained postures were operationalized as postures in which the employee had to bend down, to squat, to kneel, to lay down, or to work overhead (Beermann et al., 2005). As a matter of fact, constrained postures force the employee to feel exhausted and discomforted (Bhatnager, Drury, & Schiro, 1985; Liao & Drury, 2000). In addition, bad posture has an effect on work life from a medical point of view increasing stress, pain, and injuries in turn resulting in increased sick leave and turnover of the employees (Haslegrave, 1994; Hünting, Läubli, & Grandjean, 1981; Nag, Vyas, Shah, & Nag, 2012). Positive effects cost-wise have been demonstrated when improving workplace design (Spilling, Eitrheim, & Åaras, 1986). However, do constrained postures also affect performance in terms of processing speed and errors?

Bhatnager et al. (1985) tested the influence of three postural conditions caused by different screen heights on posture, postural discomfort, and performance in a visual inspection task. They propose an association between workplace changes, which induced postural changes, and performance. Results showed an increase of detection error by only 2 % between worst and best workplace condition. Also, participants' trunk angle was related to postural comfort and performance.

Liao and Drury (2000) conducted a study to provide further evidence of the interrelationships between posture, discomfort, and performance. Six Participants performed a typing task of 2 h while keyboard height was manipulated. They found an effect of keyboard height on posture and on postural discomfort. The effect of postural shift and postural discomfort had only a weak adverse effect on error rate as an indicator of performance. Although this study lasted for 2 h, evidence regarding the relationship between posture and performance remained weak.

Our study was also meant to analyze the relationship between posture and performance. It dealt with short-term strain evoked by constrained postures that are relatively common in technical or manual vocational areas (e.g., assembly work with screws or welding operations). In our experiments participants either sat or kneeled when operating a control device either in their front or in their back. Working behind the back is not in an easily accessible reach envelope (Wickens, Lee, Liu, & Becker, 2004) and working in a kneeling position is considered to be among constrained postures (Beermann et al., 2005).

Cognitive performances with these postures were gathered with the well-established Simon task (e.g., Simon & Rudell, 1967; Simon & Small, 1969; for an overview see Proctor & Vu, 2006). In our task, participants pressed a left key to a low-pitched tone and a right key to a high-pitched tone (or vice versa according to a balanced design), while tones were presented randomly to the left or right ear. Although tone location is irrelevant for the task, it is known to affect performance. The irrelevant spatial information remains effective even when it belongs to a different spatial event (Hommel, 1996; Shiu & Kornblum, 1999) or to a different task (Müsseler, Koch, & Wühr, 2005; Müsseler, Wühr, & Umiltá, 2006). For our mapping, this resulted in a benefit regarding reaction time and acuity for spatially corresponding conditions (left low-pitched tone requiring a left response and right high-pitched tone requiring a right response) compared with spatially non-corresponding conditions (right low-pitched tone and left response and left high-pitched tone and right response).

Taking into account previous findings in the literature, we came to different hypotheses comparing spatial stimulus–response compatibility in the two operating directions. In the front, spatial correspondences were obvious and we expected the usual Simon effect. In the back, however, findings led to deviating predictions. On the one hand, experiments with crossed and uncrossed hands seem to indicate that the correspondence between stimulus location and response location (i.e., key location) determines compatibility (e.g., Roswarski & Proctor, 2000; Wallace, 1971). Thus, the key behind participants' left shoulder should be assigned with a left code producing a similar Simon effect as in the front condition. On the other hand, coding in the back may result from the observer's virtual turn towards the keys. In this case, the key behind the left shoulder should be assigned with a right code, indicating compatibility to a right tone.

Evidence for this latter view comes from directional compatibility studies by Worringham and Beringer (1989, 1998). Participants moved a display cursor into targets with a joystick, varying their posture relative to the display across the experiment. In one condition, participants glanced over their left shoulder while operating the joystick on an outstretched right arm at the opposite side. Results showed that joystick movements were initiated faster when a movement of the display cursor to the right resulted from a joystick movement to the right corresponding to the participant's view when turned towards the joystick. Worringham and Beringer (1998) called this "visual-field compatibility."[1]

In the present paper we differentiated two alternative implementations of the visual field assumption, the "front-device coding hypothesis" and the "effector-coding hypothesis." The front-device hypothesis assumes that for spatial coding in the back the device is being envisioned from a frontal position. Thus spatial coding in the back maintains the spatial codes of the device as if it was positioned in front. The effector-coding hypothesis stresses that spatial codes are assigned on effector level, no matter if a device is operated in front or in the back of the body. In terms of the front-device hypothesis, this means for one-handed operating of the device that the "left" side of the device maintains its spatial code also in the back although it is then positioned behind the right shoulder. In terms of the effector-coding hypothesis, this means that the "left" finger remains to be coded as the "left" finger also in the back. This would then result in an inverted Simon effect in the back for both hypotheses for one-handed operating. In Experiment 3, we set out to test both hypotheses against each other by including a two-handed operating condition. Here, the two hypotheses predict different results.

Howsoever, the studies of Worringham and Beringer (1989, 1998) were different from the present study in two aspects, at least. First of all, they used a target acquisition

[1] Note that this research can be related to the field of level II perspective taking. See Kessler and Thomson (2010) and Moll and Meltzoff (2011) for an elaboration on the topic and Janczyk (2013) for evidence of costs of mental self-rotation.

task with several possible directional movements, which is much more complex than the typical two-choice key-pressing task widely used in compatibility research. Furthermore, the present study realizes a special variant of a compatibility task, i.e., the Simon task with an irrelevant spatial stimulus dimension. Second, to our knowledge response coding has never been examined in the back. The most extreme posture Worringham and Beringer (1989, 1998) included in their studies was looking to the left while operating the control device at the opposite side as described above. In that condition, spatial coding of hand movements with the hand placed at the side of the body is necessary. In contrast to that, our study induces the need to code keys in the rear space. It remains to be examined if that operating direction is comparable to a sideways direction regarding the spatial associations of the keys.

In regard to performance expectations comparing the two body positions of sitting and kneeling, several studies suggest that increased muscle tension leads to shorter reaction times (e.g., Kimura, Imanaka, & Kita, 2002; Sanders, 1980, 1998; Spijkers, 1990). Operating in a kneeling position as well as in the back should evoke increased muscle tension and thus shorten reaction times in our study, too. If so, the Simon effect, i.e., the difference between non-corresponding and corresponding trials, is expected to increase, as other studies demonstrate larger Simon effects with shorter reaction times (e.g., Hommel, 1994; Proctor, Miles, & Baroni, 2011; Wascher, 2005).

The subsequent experiments examined the relationship between body posture and cognitive processes in an auditory Simon task with two input devices. In Experiment 1, participants were asked to respond by pressing the keys on a rocker switch. In Experiment 2, the rocker switch was replaced by a round control knob, which was to be grabbed from above simulating turning behavior. Experiment 3 was run to dissociate spatial coding of the effectors and the device in rear space by including device operations with one and two hands.

Experiment 1

Participants were asked to respond to auditory stimuli (low- or high-pitched tones) presented monaurally to the left or right ear by pressing the left or right key of a rocker switch with the index or middle finger of their right hand.[2] While responding, participants operated the rocker switch either in their front or in their back and either sat on a chair or kneeled on the ground. To measure perceived musculoskeletal exertion with these postures, participants were asked to complete the Borg scale questionnaire afterwards (Borg, 1982; DIN EN ISO 9241-9, 2000, p. 42).

With regard to the visual-field hypothesis, we expected an inverted Simon effect in the back in the sense that spatial codes were generated as if turning virtually towards the device. In other words, the key closest to the participant's left shoulder is assigned with a right code and vice versa. With regard to sitting and kneeling, we expected shorter reaction times in the kneeling posture due to the increased muscle tension and—as a consequence—an increased Simon effect.

Method

Participants

Sixteen students (14 female) from RWTH Aachen University participated in the experiment. Their mean age was 21 years (SD 1.59) ranging from 19 to 24 years. All participants reported normal hearing abilities. Participants gave informed consent and were rewarded with credit points.

Apparatus and stimuli

The experiments were run on a Macintosh computer with the Matlab Software Package using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Participants wore headphones (Philips Stereo Headphone SBC HP090). A high- and a low-pitched tone were used as imperative stimuli and were presented to the left or right ear (the task-irrelevant stimulus location in the Simon task). The low-pitched tone consisted of 440 Hz and the high-pitched tone of 1,000 Hz lasting for 50 ms. In case of an error or slow response, two beeps were presented in close succession to both ears. The beeps consisted of 720 Hz tones of 50 ms each with a break of 50 ms in between them. As response, participants were asked to press the left or right side of a rocker switch which was attached to a board on which the hand rested.

Procedure

Each trial started with the presentation of the imperative auditory stimulus to either ear. Participants were asked to respond to the stimulus by pressing the respective side of the rocker switch with the index or middle finger of their right hand. In cases of an error or slow response (RT $>$ 1,000 ms), a feedback signal followed as soon as the key was pressed. After the feedback signal, there was a

[2] Note that Simon (1968, as cited in Simon, 1990) as well as Heister, Ehrenstein and Schroeder-Heister (1987) demonstrated the existence of the Simon effect with two fingers of one hand. More recent evidence comes from a study by Cho and Proctor (2010).

break of 3,000 ms before the next tone. In error free trials, the intertrial interval was 1,500 ms.

Participants were asked to perform the task blockwise either while being seated at a desk or while kneeling on a yoga mat. Further, the rocker switch was either centrally located in front of the participant or in their back. When the rocker switch was positioned in the back, participants were asked to turn their right arm backwards, so that their palms faced downwards. Changing postures happened without wrist rotation or switch of finger thus rocker switch sides and finger mapping remained constant. Throughout the experiment and with the idea to prevent possibly distractive or strategically used visual input, participants were asked to wear a sleeping mask.

Participants were instructed to respond as fast and accurate as possible. Instructions were held neutrally without mentioning direction words (left or right). Instead, the experimenter used descriptions such as "please press the key under your index finger." This was to eliminate possible priming influences when turning the hand around for backward responses.

After every block participants filled in the Borg scale questionnaire to measure perceived musculoskeletal exertion (Borg, 1982; DIN EN ISO 9241-9, 2000, p. 42). The scale consists of an 11-point scale anchored by verbal expressions ranging from 0 (no exertion at all) to 10 (very strong exertion near the maximum). Answers from previous blocks were not accessible for participants. The experiment consisted of four blocks with 144 trials each and lasted about 40 min.

Design

Body position (sitting, kneeling) and operating direction (front, back) were varied blockwise within subjects. In one block participants were seated with the rocker switch in front of them, in the next one with the switch in their back and the same for kneeling. The order of blocks was counterbalanced and randomized across participants with the restriction that body position would always double (sitting, sitting, kneeling, kneeling or vice versa). Participants were randomly assigned to one of two stimulus–response mappings. Half of the participants responded to a low-pitched tone with a left response and to a high-pitched tone with a right response. This mapping was reversed for the other half of participants. High- and low-pitched tones and tone location were counterbalanced over all blocks and presented in randomized order. Thus compatibility (compatible spatial stimulus–response location, incompatible location) was varied randomly within each block. As dependent variables response times and errors were gathered.

Results and discussion

Subjective musculoskeletal exertion

To ensure the existence of perceived differences in posture as basis for analyzing differences in performance, Borg scale rating data were analyzed. There were two significant main effects in a two-way ANOVA with body position and operating direction as within-subjects variables. The effect of body position became significant with $F(1,15) = 42.47$, $p < 0.001$, $\eta_p^2 = 0.74$ demonstrating that kneeling was perceived as being more demanding than sitting (mean scale value of 5.47 vs. 2.09). Additionally, operating in the back of the body (4.69) was significantly more demanding than operating in front (2.88) with $F(1,15) = 37.43$, $p < 0.001$, $\eta_p^2 = 0.71$. An interaction was not observed, $F < 1.00$, $p > 0.999$. These results provide evidence for the existence of perceived differences in constrained postures in regard to musculoskeletal exertion.

Response times and error percentages

Only trials with RTs in between 100 and 1,000 ms were considered in this study (exclusion rate of 3.5 % of overall trials, herewith only incorrect responses within this RT interval and no slow responses were considered for error analysis). Mean RTs of correct responses were entered in a three-way analysis of variance (ANOVA) with body position, operating direction, and compatibility as within-subjects variables. Figure 1 displays the means of the full design: RTs are marked with blank and error percentages with filled symbols. The only significant effect was the interaction of operating direction and compatibility, $F(1,15) = 52.71$, $p < 0.001$, $\eta_p^2 = 0.78$. The expected Simon effect was observed when participants operated in front of the body: mean RT was 441 ms when stimulus location and response location were compatible, and 485 ms when they were incompatible. A post hoc conducted two-tailed t test confirmed the regular Simon effect, $t(15) = 9.70$, $p < 0.001$. However, operating in the back resulted in the reversed pattern of results: Mean RT was 476 ms for the compatible condition and 439 ms for the incompatible condition, $t(15) = 4.53$, $p < 0.001$. Note in Fig. 1 that spatial compatibility in the back is defined with regard to the left/right shoulder. As the incompatible condition yielded the shortest reaction times in the back, participants' coding was identical to the spatial coding when turning towards the rocker switch and operating it as if the control device was located in front of the body. This was expected by the visual-field hypothesis. Other significant effects were not observed, $F < 2.08$, $p > 0.169$.

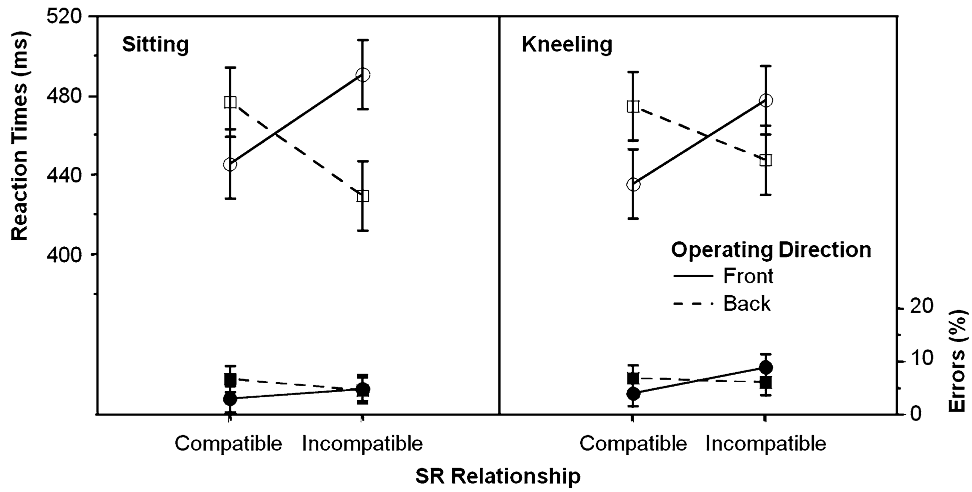

Fig. 1 Response times (*left y*-axis, *blank symbols*) and error percentages (*right y*-axis, *filled symbols*) for operating direction (Front vs. Back) and compatibility while sitting (*left panel*) and while kneeling (*right panel*) in Experiment 1. *Error bars* indicate 95 % confidence intervals according to Pfister and Janczyk (2013); see also Loftus and Masson (1994), p. 482. See text for further explanation

A corresponding ANOVA with error percentages showed no significant effects, neither in the main effects nor in the interactions, $F < 2.34$, $p > 0.147$. However, there was a trend towards an interaction of operating direction and compatibility, $F(1,15) = 3.51$, $p = 0.081$, $\eta_p^2 = 0.19$. Mean error percentages indicate lower values for compatible than incompatible trials when operating the device in front (3.5 vs. 6.9 %), $t(15) = 1.74$, $p = 0.102$, and higher values for compatible than incompatible trials when operating the device in rear space (6.8 vs. 5.3 %), $t(15) = 1.28$, $p = 0.220$. This pattern matches the results of the RT analysis and thus provides evidence for the visual-field hypothesis. We will evaluate and discuss the results together with the findings of Experiment 2 and Experiment 3 in the "General discussion".

Experiment 2

In the present experiment, the rocker switch was replaced by a small control knob resembling right-handed (clockwise) and left-handed (counterclockwise) turning behavior. However, operating a knob does not show as clear left–right associations as wheel rotations do. When turning a wheel in one direction, its top and bottom parts move easily noticeable in opposite directions. As the knob is smaller, depending on the grip of the knob, fingers and thumb will move in opposite directions making spatial coding—an essential part of the Simon effect—less intuitive.

Wang, Proctor, and Pick (2003) investigated the spatial relationship between S-R compatibility and wheel-rotation movements in a Simon task. This question was first raised in a study by Guiard (1983) (as cited in Proctor & Vu, 2006; Wang et al. 2003; see also Murchison & Proctor, 2013) and replicated as well as extended by Wang et al. (2003). Both studies showed evidence for a Simon effect when participants held the wheel at the middle or at the top position—clockwise movements referred to stimuli from the right and counterclockwise movements corresponded to stimuli from the left. For the grip at the bottom position, the studies yielded differing results. Guiard (1983) found the opposite effect compared to the middle position—stimuli from the right were associated with counterclockwise movements and vice versa. Wang et al. (2003) found no homogenous effect when looking at the bottom position. They rather found it depended on the wording of instructions emphasizing hand or wheel movements. The results suggested a conflict between reference frames caused by the influence of the task's nature as well as instructed action goals.

When operating a screwdriver or a small knob as used in the present experiment, we assumed that left–right associations corresponded to the findings of the wheel when held at the middle or top position. Correspondingly, the expectations of Experiment 1 were maintained.

Method

Participants

Sixteen new students (12 female) participated in Experiment 2. Their mean age was 23 years (SD 3.27) ranging from 18 to 31 years.

Apparatus, stimuli, and procedure

These were the same as in Experiment 1, except for the use of a control knob. This control knob was of 3 cm diameter. RTs were registered as soon as the knob was turned 45° in one direction. Participants were instructed to grab the knob with four fingers from above.

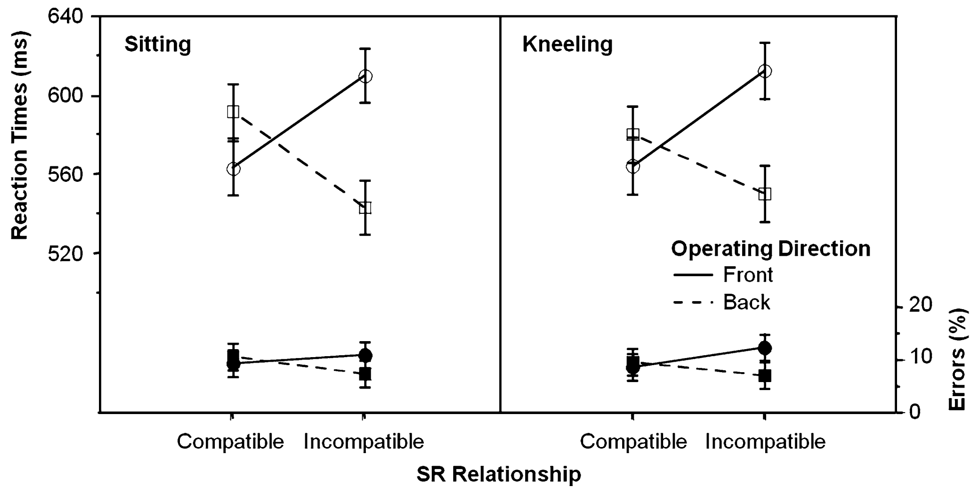

Fig. 2 Response times (*left y*-axis, *blank symbols*) and error percentages (*right y*-axis, *filled symbols*) for operating direction (Front vs. Back) and compatibility while sitting (*left panel*) and while kneeling (*right panel*) in Experiment 2. *Error bars* indicate 95 % confidence intervals according to Pfister and Janczyk (2013)

Participants were asked to respond to the auditory stimuli by turning the control knob clockwise or counterclockwise. The direction words "left" or "right" were not used in the instructions. Half of the participants responded to the low-pitched tone with a clockwise movement and to the high-pitched tone with a counterclockwise one. This mapping was reversed for the other half of participants.

Results and discussion

Subjective musculoskeletal exertion

With regard to Borg scale ratings, the main effect of operating direction became significant with $F(1,15) = 20.55$, $p < 0.001$, $\eta_p^2 = 0.58$: Operating in the back of the body was perceived as being more demanding than operating in front (5.22 vs. 3.33). However, the interaction of body position and operating direction was also significant with $F(1,15) = 43.40$, $p < 0.001$, $\eta_p^2 = 0.74$: When operating in front, kneeling was perceived as more demanding than sitting (4.22 vs. 2.44), but when operating in the back, kneeling was perceived less demanding than sitting (4.63 vs. 5.81). It is likely that this was caused by increased muscle tension in the upper arm and shoulder due to the need of raising the arm to reach the operating device on the table while sitting. The main effect of body position was not significant, $F(1,15) < 1.00$, $p = 0.508$.

Response times and error percentages

Trial discard followed the same routine as in Experiment 1, resulting in 6.7 % trial exclusion. Figure 2 shows the means of the full design: RTs are indicated by blank symbols and error percentages by filled symbols. The three-way ANOVA of mean RT showed a significant main effect of operating direction with $F(1,15) = 6.14$, $p = 0.026$, $\eta_p^2 = 0.29$. Mean RTs decreased for the operating condition in the back of the body (570 ms) compared to the front (592 ms). This decrease of reaction times, when operating in the back, could result from the higher muscle tension due to the constrained position (e.g., Kimura et al. 2002; Sanders, 1980, 1998; Spijkers, 1990).

Additionally, an interaction of operating direction and compatibility with $F(1,15) = 24.90$, $p < 0.001$, $\eta_p^2 = 0.62$ was significant. The expected regular Simon effect was observed when participants operated in front of the body: mean RT was 567 ms, when stimulus location and response location were compatible, and 616 ms, when stimulus location and response location were incompatible, $t(15) = 4.70$, $p < 0.001$. And—as in Experiment 1—operating in the back yielded the reversed pattern of results: mean RT was 589 ms for the compatible condition and 550 ms for the incompatible condition, $t(15) = 4.65$, $p < 0.001$. Thus, participants' coding was again identical to the spatial coding when operating in front of the body. This was expected by the visual-field hypothesis.

The interaction of body position and compatibility was also significant with $F(1,15) = 4.98$, $p = 0.041$, $\eta_p^2 = 0.25$. Mean RTs for compatible and incompatible conditions did not differ when sitting (585 and 584 ms), $t(15) = 0.09$, $p = 0.927$, but when kneeling, incompatible conditions showed an increased mean RT (582 ms) compared to the compatible condition (571 ms), $t(15) = 2.65$, $p = 0.018$.

The ANOVA with error percentages yielded a significant interaction of operating direction and compatibility with $F(1,15) = 7.71$, $p = 0.014$, $\eta_p^2 = 0.34$. In front, compatible trials were less error-prone than incompatible

(8.9 vs. 11.6 %), $t(15) = 3.02$, $p = 0.009$, whereas in the back, compatible trials yielded more errors than incompatible (10.0 vs. 7.2 %), $t(15) = 2.02$, $p = 0.061$, confirming the corresponding finding in RTs. Other effects in RTs or errors were not observed, max. $F < 2.76$, $p > 0.118$.

Overall, the present results replicated successfully the findings of the previous experiment and provide further evidence for the visual-field hypothesis. In Experiment 3, we checked whether a virtual turn of the observer towards the control device (front-device hypothesis) is needed or whether the spatial coding along the observer's hand was sufficient to produce the observed effects (effector-coding hypothesis).

Experiment 3

Results of Experiment 1 and 2 tend to provide evidence for the visual-field hypothesis. To examine if this finding is evoked by the virtual turn towards the device in the back (front-device hypothesis) or by the turn of the effector to the back (effector-coding hypothesis), we compared operating the rocker switch with one hand and with two hands in the present experiment. With this manipulation the spatial coding of the device and the spatial coding of the effectors changed from front to rear space with two-handed operating. The right hand operating the right side of the rocker switch in front was operating the former left side of the rocker switch in rear space. Thus, the front-device hypothesis, where the side of the device is identical front and back, and the effector-coding hypothesis, where the spatial coding of the effector carries over, was made dissociable. If the front-device hypothesis held true, we expected, again, reversed Simon effects when operating the device with two hands in the back. However, following the effector-coding hypothesis, we expected a regular Simon effect when operating the device with two hands in the back.

Method

Participants

Sixteen new students (8 female) participated in Experiment 3. Their mean age was 27 years (SD 7.79) ranging from 19 to 49 years.

Apparatus, stimuli, procedure, and design

Apparatus and Stimuli were the same as in Experiment 1. For the procedure, participants responded while sitting blockwise with either two fingers of the right hand (index and middle finger) or two hands with each one finger (index finger) in front or in the back of their bodies. The design was similar to Experiment 1 except for the substitution of the variable body position by the variable number of hands.

Results and discussion

Subjective musculoskeletal exertion

Results of Borg scale ratings show a significant main effect of operating direction, $F(1,15) = 16.78$, $p = 0.001$, $\eta_p^2 = 0.53$. Operating the device in front was perceived less demanding than operating it in rear space (1.97 vs. 3.25). All other effects were not significant with $F < 1.00$, $p > 0.589$.

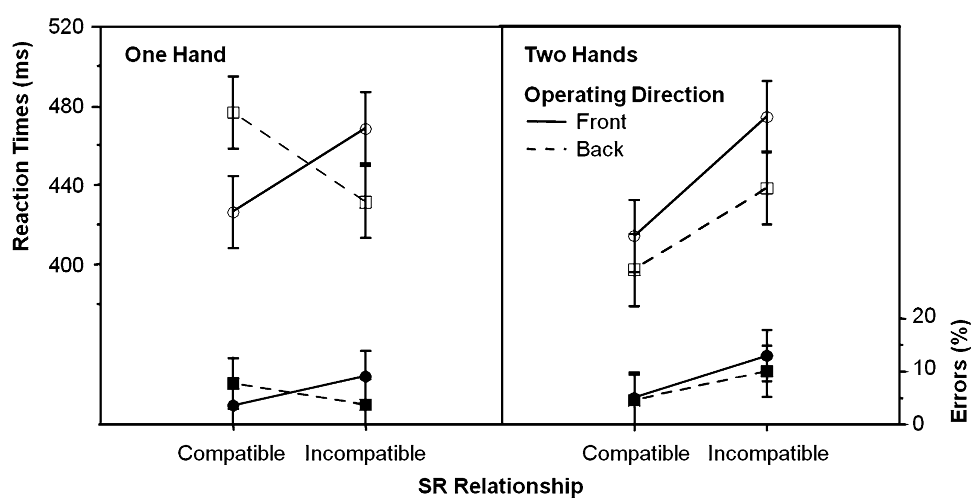

Fig. 3 Response times (*left y*-axis, *blank symbols*) and error percentages (*right y*-axis, *filled symbols*) for operating direction (Front vs. Back) and compatibility while operating with one hand (*left panel*) and two hands (*right panel*) in Experiment 3. *Error bars* indicate 95 % confidence intervals according to Pfister and Janczyk (2013)

Response times and error percentages

1.9 % of all trials were discarded exceeding the RT restrictions (as in Experiment 1 and 2 trials with RT between 100 and 1,000 ms). In Fig. 3, the means of the full design are displayed: RTs are depicted with blank symbols and error percentages with filled symbols. For RT data, the three-way ANOVA showed a significant main effect of compatibility, $F(1,15) = 17.69$, $p = 0.001$, $\eta_p^2 = 0.54$. Responses in compatible trials were faster than in incompatible trials (428 vs. 453 ms). The significant two-way interactions of operating direction and compatibility, $F(1,15) = 11.76$, $p = 0.004$, $\eta_p^2 = 0.44$, and of number of hands and compatibility, $F(1,15) = 22.49$, $p < 0.001$, $\eta_p^2 = 0.60$, and the trend in operating direction and number of hands, $F(1,15) = 3.42$, $p = 0.084$, $\eta_p^2 = 0.19$, will not be interpreted as the three-way interaction became significant with $F(1,15) = 16.21$, $p = 0.001$, $\eta_p^2 = 0.52$. When analyzing the respective mean RTs separately per number of hands post hoc, the same disordinal interaction of operating direction and compatibility of Experiments 1 and 2 becomes apparent for the one-hand condition, $F(1,15) = 20.50$, $p < 0.001$, $\eta_p^2 = 0.58$. When operating in front, compatible trials yield shorter RTs than incompatible ones (426 vs. 468 ms), $t(15) = 3.32$, $p = 0.005$, whereas when operating in the back, incompatible trials cause faster responses than compatible ones (431 vs. 476 ms), $t(15) = 5.34$, $p < 0.001$.

Considering the two-hand condition, the interaction of operating direction and compatibility is not significant, $F(1,15) = 1.52$, $p = 0.237$, $\eta_p^2 = 0.09$. The main effects of operating direction and compatibility were significant with $F(1,15) = 5.59$, $p < 0.032$, $\eta_p^2 = 0.27$ and $F(1,15) = 24.64$, $p < 0.001$, $\eta_p^2 = 0.62$. When operating in front, responses are significantly faster in compatible trials than in incompatible ones (414 vs. 474 ms), $t(15) = 4.27$, $p = 0.001$, as well as when operating in the back (397 vs. 438 ms), $t(15) = -3.46$, $p = 0.003$, and generally faster in the back.

The non significant effects in RT (main effects of operating direction and number of hands) were $F < 2.83$, $p > 0.113$.

The respective three-way ANOVA for error rates yielded a significant main effect of compatibility, $F(1,15) = 7.19$, $p = 0.017$, $\eta_p^2 = 0.32$, and an interaction of number of hands and compatibility, $F(1,15) = 6.13$, $p = 0.026$, $\eta_p^2 = 0.29$. The main effect indicates a regular compatibility effect with generally lower error rates for compatible trials than incompatible ones (4.9 vs. 8.6 %). The interaction indicates that the compatibility effect was not significant when operating with one hand, $t(15) = 0.93$, $p = 0.369$, (compatible vs. incompatible trials: 5.3 vs. 6.0 %), but was significant when operating with two hands, $t(15) = 2.70$, $p = 0.016$, (4.5 vs. 11.2 %). Other effects were not significant, $F < 2.56$, $p > 0.131$.

As can be seen from the significant three-way interaction in RT, there are major differences in how spatial codes are applied to the responses in rear space. When operating the rocker switch with only one hand, the visual-field hypothesis seems to apply and spatial codes in rear space correspond to the codes as if the operator turned around virtually and sees the device and the effector from a frontal perspective (the finger assigned formerly to a left response retains this spatial code although it is located on the right side of the participant when operating in the back). However, when operating the switch with two hands in rear space, results indicate a different pattern. Then the hands also retain their spatial coding from the frontal perspective as seems to be a natural behavior as extremities do not change their spatial coding in reference to the body. Yet, the left hand corresponds to the formerly right side of the device. In the finding of a regular Simon effect in rear space, we can see that participants neglected the former spatial coding of the rocker switch itself. Instead, they coded space along the spatial codes on effector level. This is not in line with the hypothesis of the front-device compatibility, but with the hypothesis of the effector-coding compatibility.

General discussion

The objective of the current study was to clarify the influence of constrained postures on cognitive processes, here on spatial compatibility measured by an auditory Simon task. Participants responded to the pitch of left/right tones operating a rocker switch (Experiment 1) or a control knob (Experiment 2) either in front or in the back of their bodies (operating direction) and while sitting or kneeling (body position). Experiment 3 was meant to specify the results of the first experiments in terms of spatial coding in rear space. This was done by comparing a one-hand and a two-hand condition in the original set up.

Taken the results of the subjective Borg scale ratings of all experiments together, we see that the constrained postures we used indeed caused a decrease in perceived comfort. Operating in the back was perceived more demanding across all experiments. Kneeling was consistently only more demanding when operating in front. In Experiment 2, sitting while operating in the back was most demanding probably due to the joint angle. Although the posture manipulations had an effect on perceived comfort, the effect of posture on performance was minor. In

Experiment 2, the interaction of body position and compatibility indicated that kneeling induced stronger compatibility effects than sitting. However, our prediction was that stronger compatibility effects in constrained positions should result from a general decrease in reaction times due to the increased muscle tension and—as a consequence—of a higher activation of the spatial code with short reaction times (e.g., Hommel, 1994; Proctor et al. 2011; Wascher, 2005). This was not observed overall. A decrease of reaction times was only observed when operating in the rear space in Experiment 2, which could result from the higher muscle tension due to constrained position (e.g., Kimura et al. 2002; Sanders, 1980, 1998; Spijkers, 1990). However, this decrease in reaction time was not accompanied by an increase of the compatibility effect. The short duration of each constrained posture could serve as a possible explanation for the absence of a stronger effect of posture on performance. This is in line with Liao and Drury (2000) who also mentioned the short duration as a possible reason for the absence of stronger effects.

Major findings of Experiment 1 and 2 are consistent in terms of performance. Operating a rocker switch or a control knob did not change the spatial coding. Note that the participants' instructions stressed to move the knob clockwise or counterclockwise, not rightward or leftward. Nonetheless, the Simon effects were significant in both experiments and descriptively of about equal size suggesting that clockwise movements are coded as rightward movements and counterclockwise movements as leftward movements. In this respect, turning a small knob seems to be similar to turning a wheel when held at the top or side position (cf. Guiard, 1983; Murchison & Proctor, 2013; Wang et al., 2003).

The interaction of operating direction and compatibility, coherently found across Experiment 1 and 2, seems to provide evidence for the visual-field hypothesis. In front of the body, participants were faster and more accurate when the response location (left/right press of the rocker switch or leftward/rightward movement of the knob) as indicated by the pitch of a tone corresponded to the left/right ear at which this tone was presented (Simon effect; e.g., Simon & Rudell, 1967; Simon & Small, 1969). When operating in the back, this result was reversed. Then, participants' coding seemed to be identical to the spatial coding that they used in front of their bodies as if they had aligned their bodies and the device mentally to a frontal position (similar to level II perspective taking, see Kessler & Thomson, 2010; Moll & Meltzoff, 2011). This means that the key next to the left shoulder was coded as right and vice versa and was expected by the visual-field hypothesis (cf. Worringham & Beringer, 1989, 1998).

As instructions specified arm and hand positioning, this reversed effect cannot be due to different hand orientations or grips controlling the rocker switch or the knob. In both experiments, participants were asked to move the arm to the back without turning the wrist. A grip difference accounting for differences in compatibility perception as suggested by Wang et al. (2003) should have been prevented. Also, the differences in data patterns of perceived comfort between the experiments (significant main effects vs. significant interaction) should not have undermined the results of performance, because here results are consistent and do not seem to vary with the respective variations in subjective musculoskeletal exertion.

However, results of Experiment 3 lead to a differentiated picture. Here, we intended to disentangle the spatial coding relatively to the device and the spatial coding relatively to the effector. In rear space, we found an inverse Simon effect when operating the device with one hand, thus replicating results of Experiment 1 and 2. Yet when operating the device with two hands, the Simon effect turned out regular. This finding is not in line with the front-device hypothesis, which would always predict an inverse Simon effect in rear space: When operating in the back, the side behind the right shoulder should correspond to sounds from the left and vice versa. Results from two-hand device operating in the back, however, suggest that the side behind the right shoulder corresponds to sounds from the right. It becomes apparent that in general (not restricted to two-handed operating) spatial coding in the back does not depend on how the sides of the device were coded with respect to the frontal position, but it depends on how the effectors are coded (in front).

Conclusions

When designing workplaces in which employees need to access rear space, it is important to align spatial codes with the spatial coding of the effectors and not the device.

There is enough evidence from the medical and vocational perspectives that constrained postures cause manifold disadvantages to continue improving workplace design. In the present study, we observed minor effects on cognitive performance. However, this might originate from the short duration of obtained postures (sitting and kneeling).

Acknowledgments We would like to thank Markus Janczyk, Robert Proctor, and Bernhard Hommel for their valuable and constructive comments on an earlier version of the manuscript. Correspondence concerning this article should be addressed to either author at the Institute of Psychology, RWTH Aachen University. Email: kreutzfeldt@ or muesseler@psych.rwth-aachen.de.

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