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Referential Coding of Steering-Wheel Button Presses in a Simulated Driving Cockpit

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The present study investigated whether left and right pushbuttons on a steering wheel are coded relative to an "infotainment display" in a simulated driving cockpit. Participants performed a go/no-go Simon task in which they responded on trials for which a tone, presented from a left or right speaker, was 1 of 2 pitches (low or high) with a single button press (left in 1 trial block; right in another). Without the infotainment display in Experiment 1, both left and right responses showed Simon effects of similar size. In both Experiments 2 and 3, the infotainment display was located to the right or left, and the Simon effect was smaller for the response that was on the side of the infotainment display than for the response that was on the opposite side. The results indicate that in a driving cockpit environment, the pushbutton responses are coded as left and right with respect not only to the wheel-based frame but also to a salient object like the infotainment display. The general point for application is that the driver's spatial representation of responses, and consequently performance, can be influenced by multiple frames of reference.

Keywords: multiple reference frames, Simon effect, social Simon effect, steering-wheel button responses, stimulus–response compatibility

Gibson and Crooks (1938) described driving as a type of locomotion through a field of space and the task of the automobile driver as predominantly a spatial perceptual-motor task. Indeed, no one would doubt the importance of the spatial dimension, at least outside the vehicle, during driving. With the development of electronics technology in the latter 20th century, more and more sophisticated systems have been placed inside the motor vehicle, including the multifunction instrument cluster display behind the steering wheel and a head-up display projected on the front windshield to improve driving safety and efficiency, and the centrally located infotainment system to improve the driver's comfort (Kern & Schmidt, 2009). Therefore, the space within the vehicle has become increasingly complex.

The interactions of the driver with these systems are crucial, as they may improve the driving experience or distract the driver from the primary driving task. Steering-wheel buttons or thumbwheels are now widely used to control the systems' functions remotely because they can be reached without moving the hands off the steering wheel, which improves driving safety by reducing visual distraction time and operation time (Makiguchi, Tokunaga, & Kanamori, 2003). As the driver operates these systems with the steering wheel's left or right buttons inside the vehicle, it is essential to investigate how the horizontal spatial dimensions provided by these added systems impact the interactions with the steering-wheel buttons on each side.

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Steering-Wheel Controls

A few prior studies have investigated effects of the number of steering-wheel controls and their arrangement. Murata and Moriwaka (2005) examined how the arrangement and number of steering-wheel buttons interactively affect performance. One button from a left-side vertical column had to be selected for a particular function (e.g., to operate the radio) and a right-side button (one of four, labeled with arrows) was used to execute specific commands. Performance was best with only three function buttons and a cross-type arrangement of the four command buttons. Mossey (2013) had drivers of ages 18 to 29 years and 47 to 65 years choose which functions to place on the steering wheel, the controls' placements, and the preferred control type for each function. The mean number of functions chosen was about 15 and did not differ across age, gender, group, model year of current vehicle, or affinity for technology. Users wanted most controls to be pushbuttons and to keep the most critical and frequently used ones, such as cruise control functions, in the upper two spokes of the steering wheel, within thumb reach.

Steering-wheel controls' horizontal placement was also examined among different user groups in Mossey's (2013) study. The results indicated a general trend to place radio-related controls on the left side of the wheel but cruise controls on the right side, along with other performance controls. However, how and why participants were making such horizontal placement decisions was not evaluated. This preference is consistent with some automobile manufacturers' designs (e.g., 2013 Subaru Outback and 2014 Honda Accord), and a possible reason may be based on the "common sense" that a faster response can be obtained on the right-hand side because 70% to 95% of the population is right-handed (Holder, 1997). To the contrary, though, some automobile manufacturers use the opposite way of putting all driving- or performance-related controls on the left side while keeping the infotainment-related buttons on the right side, as in the 2014 Buick Regal. This arrangement is probably based on the proximity compatibility principle (Wickens & Carswell, 1995), according to which a control's location should be close to the display of the entity it controls. So, radio and related features' operations are on the right of the steering wheel, close to the infotainment system on the center display.

Murata and Moriwaka (2007) investigated display-control proximity compatibility by manipulating display location (display on the left side of the participant or in front) and control location (to the left of the participant or on the steering wheel) for younger and older adults. Participants performed a dual-task experiment in which the primary task was first-order tracking, in which participants operated the steering wheel to track a visual display shown by a front projector. The secondary tasks included operation of the air conditioner, the radio, and a compact disk player by means of a steering-wheel-mounted switch or a left-located console-mounted switch. Results showed that the proximity compatibility principle was applicable for both the front- and left-positioned displays for the older group (i.e., they responded quickest when the display and control positions matched), but it did not apply to the left display of the young age group, for which faster responses were obtained by steering-wheel controls rather than left-side controls. The authors explained that the proper grouping as a result of display-control proximity compensated for the decline in perceptual and cognitive functions for the older adults, which reduced the response time. With the advantage of steering-wheel-mounted buttons confirmed, the ineffectiveness of display-control proximity compatibility for the younger adults when using the left display was not further explained. As buttons are located on the left and right of the steering wheel as well, the results of this study suggest that the proximity compatibility principle may be ineffective when using a left-side steering-wheel button with the left display.

In Murata and Morikawa's (2007) study, numeral and arrow buttons fixed on the left and right sides, respectively, were placed around the steering wheel or on a console to the left of the participant. In the left-display condition, the left-side switch was placed between the left display and the participant. Even though it was called the "left switch" by the authors, there were multiple spatial frames in the simulated driving cockpit that could render the spatial coding of the switch from left to right. First, the left switch was composed of two parallel groups of left buttons and right buttons locally. Second, the switch could be coded as left based on the participant's seat position. Third, it could also be coded as right relative to the display's location. In contrast, there was no conflict in the spatial coding of the steering-wheel controls with the front display.

Spatial Referential Coding

Multiple horizontal spatial dimensions exist inside the vehicle. The steering wheel offers one spatial reference frame, or object, relative to which spatial locations can be represented (Binder, Hirokawa, & Windhorst, 2009), because the buttons are located on the left and right, and are operated by the left and right thumbs, respectively. Also, dynamic events from the infotainment display, such as music information or real-time navigation map, are commonly seen inside a car during driving; thus, the centrally located infotainment system provides a salient reference that splits the vehicle's interior horizontal space into left and right. Relative to that system, the driving cockpit (driver position, steering wheel, etc.) is located to the left (for vehicles driving with right-hand traffic rules, as in the United States). The passenger seat or passenger in it provides another object relative to which the driving cockpit is located to the left.

For the left steering-wheel button, there is no conflict between spatial codes relative to the multiple reference frames because it is "left" with respect to all of them. However, for the right steering-wheel button, the coding of left relative to the infotainment display conflicts with the right position on the steering wheel. If the response position is coded relative to the nonwheel frame, this should create interference in responding with the right button compared with the left one. Whether spatial coding of the steering-wheel buttons is impacted by the location of the infotainment display, and hence influences performance, is the main concern of the present study.

The spatial dimension's influence on people's performance has been widely investigated in cognitive psychology. Spatial stimulus response (S–R) compatibility, faster reactions when the position of the stimulus corresponds with the position of the response than when it does not, is an effect that is consistent and robust (Fitts & Deininger, 1954; Proctor & Vu, 2006). Even when the spatial relation between stimulus and response is task-irrelevant, a similar benefit of spatial congruency, known as the Simon effect, also occurs (Simon, 1990; Simon & Small, 1969; for a review, see Lu & Proctor, 1995). Both S–R compatibility and Simon effects occur for visual, auditory, and tactile stimuli (Ho, Tan & Spence, 2005; Roswarski & Proctor, 2000; Simon, Acosta, Mewaldt, & Speidel, 1976). In general, spatial compatibility versus incompatibility plays an important role when people perform tasks that require responding to stimuli.

Kornblum, Hasbroucq, and Osman (1990) proposed a dual-process model to explain SRC and Simon effects that emphasizes automatic activation of the spatially corresponding response. That is, even if task-irrelevant, the stimulus position is automatically coded, which activates the corresponding response. When it is identical with the correct response, responding is facilitated, but when the two are different, the response conflict delays response selection (e.g., De Jong, Liang, & Lauber, 1994). Therefore, the Simon effect is attributable to the dimensional overlap between the task-irrelevant stimulus location and response location, which leads to activation of the corresponding response during the response-selection process (Kornblum & Lee, 1995).

Several studies (e.g., Lamberts, Tavernier, & d'Ydewalle, 1992; Roswarski & Proctor, 1996; Umiltà & Liotti, 1987) have investigated the influence of irrelevant stimulus location on button-pressing responses within the context of multiple reference frames (e.g., relative to which a stimulus is coded as left for one and right for the other; Roswarski & Proctor, 1996). Therefore, instead of two possible stimulus locations, four or more stimulus locations were provided. With consistent spatial codes, larger Simon effects were reported for the outer positions, whereas the Simon effect became smaller or disappeared when multiple spatial codes became more conflicting for the inner positions. These results demonstrate that the Simon effect (spatial compatibility) is based jointly on spatial coding with respect to multiple frames of reference.

Referential Coding in Go/No-Go Tasks

In a typical Simon task paradigm, a two-choice reaction task is conducted, with spatially defined responses (e.g., left and right response keys) assigned to a nonspatial relevant stimulus feature (e.g., red or blue color). When an individual participant responds with only one response to a single stimulus value (e.g., red, and not blue), the Simon effect is not obtained under most circumstances (Hommel, 1996). The Simon effect is attributed to response-selection processes, and the absence of Simon effect in most go/no-go Simon tasks is accounted for by assuming that the response-selection stage is bypassed when one consistent response is assigned to only one stimulus' attribute (Lu & Proctor, 1995).

Within the past decade, the Simon effect has been shown to reappear if the same go/no-go Simon task is distributed between two participants, such that each person is responding to only one stimulus value—the so called "social Simon effect" (Sebanz, Knoblich, & Prinz, 2003). In Sebanz et al.'s (2003) study, two complementary go/no-go tasks were assigned to two participants, who sat alongside each other. The stimuli were a hand with the index finger pointing to the left or right. One participant was to respond when a ring on the finger was red, whereas the other participant was to respond when the ring was green, creating an overall two-choice left–right Simon task. There was a significant Simon effect in the group setting only, which was similar to the effect obtained when a single participant had to choose between the alternative responses.

Previously, this social Simon effect has been considered to be a consequence of action corepresentation, in which the coactor's actions are cognitively integrated into the actor's own action (e.g., Tsai & Brass, 2007). Nevertheless, several findings have challenged this social copresentation account. For example, Guagnano, Rusconi, and Umiltà (2010) found that the major role of the coactor may be to provide a spatial frame of reference to the actor's peripersonal space, rendering the actor's own action as left or right. And according to Dolk et al. (2011), the "social Simon effect" could also be obtained without the human or biological coactor.

Recently, Dolk, Hommel, Prinz, and Liepelt (2013) demonstrated a "social" Simon effect in the absence of biological coactors. In their Experiments 1–4, the mechanical arm movement of a Japanese waving cat, movement of a clock, and auditory rhythm of a nonmoving metronome were provided as reference objects to the response in an auditory individual go/no-go Simon task. Any object that was salient enough to attract attention was sufficient to induce a Simon effect. These findings imply an account of the social Simon effect in terms of the spatial components inherent in the joint go/no-go Simon task, with the other participant serving as an object for referential coding of the response. Dittrich, Dolk, Rothe-Wulf, Klauer, and Prinz (2013) provided further evidence for spatial coding by identifying two spatial components, response keys and coacting agents, as influencing response coding in a joint go/no-go Simon task. They found a joint social Simon effect only when the spatial orientation (e.g., vertical) of the responding agents and response keys matched each other and the orientation of the stimuli.

In the individual go/no-go Simon task setting, no matter whether the salient object is biological or nonbiological, mainly its location matters, as it provides a spatial reference to the response. Thus, when the salient object acts as a complementary part of the response in the spatial dimension, the overlap between the stimulus and response dimensions is reinstated, as in a typical Simon task, and thus the Simon effect is observed. Furthermore, as suggested by Dolk et al. (2013), the joint go/no-go Simon effect does not necessarily require a coactor, no matter biological or nonbiological, but an object, that is salient enough to provide a frame of reference for the spatial coding of one's action.

Current Study

Returning to driving, multiple spatial frames of reference are present relative to which the locations of the steering wheel's left and right buttons could be coded. As proper button location must be taken into consideration to assure fast responses of the driver for performance and safety-related controls (Mossey, 2013; Murata, Tanaka, & Moriwaka, 2011), whether the congruency effect decreases or disappears for the steering wheel's left and right buttons in a multiple spatial frames of reference scenario needs to be investigated. The current study was designed to examine how performance of the steering wheel's left and right button responses is impacted by the multiple spatial frames of reference provided in the driving cockpit. In all experiments, participants performed an auditory go/no-go Simon task with a left or right steering-wheel button, while holding the wheel with both hands such that the thumbs from each were on the buttons. Experiment 1 was conducted without the infotainment display, which allowed us to establish a baseline level of performance and determine whether a congruency effect occurred based on this wheel-based reference frame.

In both Experiments 2 and 3, a dynamic visual display was situated to the right or left of the steering wheel, mimicking an infotainment screen for vehicles of right-hand traffic (as in China and the United States) or left-hand traffic (as in Australia and Japan). With more and more functions introduced into the infotainment system (e.g., Ford SYNC system), various interactions are required through the operation of steering-wheel button controls. Therefore, for the steering-wheel button operation, the display may act as an extra spatial referent due to its salience to the driver. The experiments differed only in that Experiment 2 included a neutral tone location condition, whereas Experiment 3 did not, and the predicted influence of the infotainment display was the same for each. If the display to the right or the left side of the steering wheel provides another spatial reference frame relative to which the responses are coded, then the congruency effect should be larger for the responses farther away from the displays (e.g., left response for the right display) than for those closer to the displays (e.g., right response for the right display).

Experiment 1

Pushbuttons are located on the left and right side of the steering wheel. According to the referential coding hypothesis, if responses are coded as left and right relative to each other, even though only one response is required in a go/no-go Simon task paradigm, congruency effects for which responses are faster when stimuli occur to the side of the go response should be evident. Thus, Experiment 1 was conducted to examine the effect of the left and right button responses.

Individual participants performed a go/no-go auditory Simon task in a simulated driving cockpit. They grasped the steering wheel with both hands in a typical driving position and placed both thumbs on buttons. Their task was to respond to tones of one of two pitches presented to the left or right with the left response in one trial block and the right response in another. In Experiment 1, for the trial block in which participants responded with the left button, a congruency effect favoring the left tone location was expected, and for the right-button block, a congruency effect favoring the right location would indicate that the responses were coded in regard to their positions on the wheel.

Method

Participants. Forty undergraduate students (31 male and nine female, with a mean age of 20 years) participated, with all but three being right-handed. All participants in this and the remaining experiments (a) were enrolled in an introductory psychology at Purdue University and received research credits, (b) reported having normal or corrected-to-normal vision and audition, and (c) were naïve to the purpose of the study. In this experiment and the others, participants were replaced if their overall percentage error (PE) was >10%, their mean reaction time (RT) was more than 2 standard deviations above the overall mean, or mean RT in the second trial block exceeded that in the first block by more than 150 ms (suggesting decreasing effort as the approximately 50-min session progressed). Applying these criteria, five participants were replaced in this experiment.

Apparatus and stimuli. Participants were seated in front of a 76-cm high table on which an Extreme Competition Controls (ECCI, Burnsville, MN) steering wheel was mounted 10° off vertical and tilted away from the participants. The distance between the seat and the bottom of the wheel was about 25 cm. Instructions, a fixation cross, and a visual response error message were presented on a 100-in. projector screen in front of participant (see Figure 1).

The stimuli were 200-Hz and 500-Hz tones of approximately 60 dB, respectively, which were the frequencies used in Experiment 1 of Hommel (1993). The tones were delivered by two speakers located in front of the steering-wheel desk, to the left and right of the participant, at a 1-m distance. The response keys were two red buttons on the top half of the steering wheel, one on the left and the other on the right, on which the thumbs of the respective hands rested while the wheel was gripped by the remaining fingers. Each participant sat centrally in front of the screen and responded to only one tone pitch (go trials), with the pitch that was used for go trials counterbalanced between participants. Stimulus presentation, response recording, and data collection were controlled by E-prime 2.0 software installed on a Dell PC workstation.

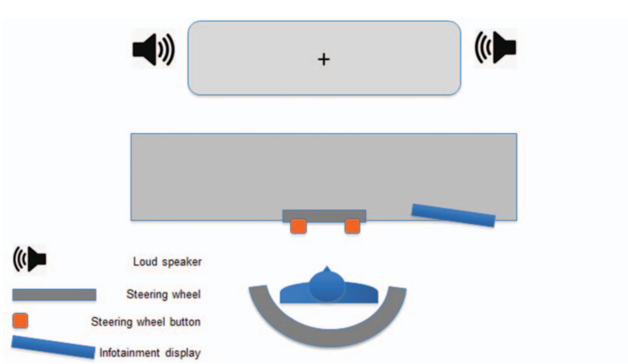

Figure 1. The experimental setting used in all experiments, with the infotainment display position to the right, as in Experiment 2A, and the right-positioned display condition of Experiment 3. No infotainment display was included in Experiment 1, and the display was positioned to the left of the steering wheel for Experiment 2B and left-positioned display condition of Experiment 3. See the online article for the color version of this figure.

Procedure. All participants were told to respond only to the assigned tone pitch (go signal) with the left response in one block and the right response in the other, with block order counterbalanced across participants. The response for a given block was designated by the experimenter pointing to it, with no reference made to left or right hand or button. For each block, the participants first completed 18 practice trials (nine go trials, nine no-go trials) that were not subjected to analysis, which were then followed by 360 experimental trials (half go trials, half no-go trials). The experimental trials in the block were presented in two parts, with a break of approximately 1 min in-between. Each part included 60 corresponding (tone presented on the same side of assigned button), 60 neutral (sound presented in both speakers), and 60 noncorresponding (tone presented on the side of button that should not be pressed) trials; each pitch occurred equally often in each location, randomized within each part. Participants were told to put both thumbs on top of the response buttons during the whole experiment and to respond as quickly and accurately as possible with the designated thumb only on the go trials.

Each trial began with a cross filling an empty circle fixation in the center of the screen for 50 ms; 500 ms after the cross's offset, a tone was presented for 200 ms via the left or right speaker, to which a response was to be made if the tone was of the designated pitch. When no response was detected, the trial was terminated 2,000 ms after the tone onset. For incorrect trials (response on no-go trials and no response on go trials), an error message was displayed for 1,000 ms. For all trials, an additional interval of 1,500 ms occurred before onset of the next trial.

Results

Mean correct RTs and PEs as a function of congruency and response location were calculated for each participant. The congruency analysis was based only on the results of go trials, for which most errors in this and the remaining experiments were omissions rather than presses of the wrong button. In this experiment and all others, trials with premature responses (RT <150 ms) or for which RT was >2.5 standard deviations above each participant's overall mean were excluded (2.5%). Neutral trials were included in the experiment as a possible baseline against which to evaluate interference on incongruent trials versus facilitation on congruent trials (e.g., Simon & Rudell, 1967). However, the results showed a general RT advantage for the neutral trials (see Table 1), replicating Sebanz et al.'s (2003) findings, and therefore did not provide an appropriate baseline. Consequently, we excluded the neutral trials in the statistical analysis for this experiment and Experiment 2 due to our main concern being the Simon effects.

Analyses for RT and PE were performed with a 2 (congruency: congruent, incongruent) × 2 (response location: left, right) analysis of variance (ANOVA), with factors being within-subjects. Initially, the ANOVA was performed with response location order (left response first or right response first) as a between-subjects factor, but because order did not produce any significant effect, we disregarded it in the reported analyses for this and the other experiments.

Response time. There was a main effect of congruency, $F(1, 39) = 35.22$, $p < .001$, $\eta_p^2 = .475$, indicating that responses were faster when tones were spatially congruent to the response location (530.5 ms) than they were not (542 ms), and congruency did not interact with response location (see Table 1), $F < 1.0$. The response location factor also showed no main effect, $F < 1.0$.

Response errors. The ANOVA of PE did not show main effects of congruency or response location, or their interaction, Fs < 1. The PE results are displayed in Table 1. Because erroneous responses also occur when the designated button is pressed on no-go trials (PE for pressing the nondesignated button on no-go trials was approximately 0% in all experiments), we conducted an additional 2 (go/no-go: go, no-go) × 2 (response location: left, right) ANOVA. It showed that more errors were commissions on no-go trials than errors on go trials (see Table 1), $F(1, 39) = 8.90$, $p = .005$, $\eta_p^2 = 0.186$. The main effect of response location and its interaction with the go/no-go term were not significant, Fs < 1.0.

Discussion

Significant Simon effects of similar size were obtained for the left and right responses of steering-wheel buttons. This Simon effect pattern indicates that the responses were coded as left and right relative to the wheel-based reference frame even though only one response was required. Whether the wheel apparatus itself or placement of the hands (and thumbs) on the wheel is responsible for the wheel-based coding cannot be determined, but showing a wheel-based effect with the hands on the wheel is sufficient for our main purpose of providing a baseline for evaluating the influence of the infotainment display in the simulated driving cockpit.

Experiments 2A and 2B

In the typical driving cockpit of a right-hand traffic vehicle, as in the United States, the driver is located to the left in the vehicle and to the left of the infotainment system. The display screen of the infotainment system presents lots of functions, such as for the Ford SYNC system, which provides various interactions with the driver through the operation of steering-wheel button controls. Therefore, for the steering-wheel button operation, the display may act as an extra spatial referent for the driver. For this reason, we conducted Experiment 2A with a simulated infotainment display placed to the right of the participant (see Figure 1). According to the referential coding hypothesis, a Simon effect for the left response, but a smaller Simon effect for the right response, should be obtained.

The stronger prediction of the referential coding hypothesis is that if the display is placed to the left side of the steering wheel, as in driving a vehicle with the steering wheel on the right, such as in Great Britain or Australia, an opposite pattern for the two response locations should be obtained, that is, the Simon effect should be larger for the right response than for the left response. Therefore, we subsequently conducted Experiment 2B, which was the same as Experiment 2A, except that the display was placed to the left side of the steering wheel. For brevity of presentation, and to emphasize this predicted interaction, we present the results for the two experiments together, with display position included as a variable.

Method

Participants. Forty undergraduate students (28 male and 12 female, with a mean age of 19 years) participated in Experiment 2A (all but three were right-handed), and 40 others (25 male and 15 female, with a mean age of 20 years) in Experiment 2B (all but four were right-handed). Five extra participants in Experiment 2A

Table 1
Mean RT and PE With Standard Errors (in Parentheses) for Congruency (Congruent, Neutral, Incongruent), Simon Effects, and No-Go Errors for Each Condition in Experiments 1–3

		RT (ms)				PE (%)				
Condition	Response location	Congruent	Neutral	Incongruent	Simon effect	Congruent	Neutral	Incongruent	Simon effect	No-go
Experiment 1										
W/O display	Left	526 (4.0)	520 (3.5)	539 (4.1)	13**	0.2 (0.09)	0.1 (0.08)	0.3 (0.12)	0.1	0.6 (0.11)
	Right	535 (4.1)	531 (3.8)	545 (3.9)	10*	0.5 (0.32)	0.3 (0.10)	0.3 (0.12)	−0.2	0.6 (0.14)
Experiment 2										
Right display	Left	515 (3.5)	512 (3.3)	527 (3.2)	12**	0.4 (0.09)	0.5 (0.11)	0.4 (0.15)	0.0	0.8 (0.12)
	Right	510 (4.0)	504 (3.6)	514 (3.5)	4	0.4 (0.11)	0.5 (0.12)	0.5 (0.12)	0.1	0.8 (0.16)
Left display	Left	511 (3.8)	506 (4.5)	519 (3.6)	8*	0.4 (0.12)	0.5 (0.11)	0.5 (0.09)	0.1	0.11 (0.17)
	Right	504 (3.4)	500 (3.9)	519 (4.2)	15**	0.4 (0.10)	0.5 (0.16)	0.6 (0.18)	0.2	0.8 (0.16)
Experiment 3										
Right display	Left	514 (5.7)	N/A	524 (6.6)	10*	1.8 (0.36)	N/A	1.9 (0.35)	0.1	0.9 (0.18)
	Right	505 (5.8)	N/A	512 (6.1)	7*	0.6 (0.27)	N/A	1.2 (0.15)	0.6	1.0 (0.25)
Left display	Left	528 (5.0)	N/A	530 (3.8)	2	0.7 (0.25)	N/A	0.9 (0.21)	0.2	0.5 (0.07)
	Right	519 (5.0)	N/A	533 (4.2)	14*	0.2 (0.13)	N/A	0.2 (0.15)	0.0	0.5 (0.11)

Note. RT = reaction time; PE = percentage error; W/O = without; N/A = not applicable. Standard errors were calculated based on Cousineau's (2005) method for within-subject variables.
* $p < .05$. ** $p < .001$.

and three in Experiment 2B were replaced, applying the same criteria as in Experiment 1.

Apparatus, stimuli, and procedure. The experimental setting, including design, task, stimuli, amount of trials, and the procedure, were the same as in Experiment 1, except as noted. The simulated infotainment display was placed to the right side of the steering wheel in Experiment 2A (right-positioned display condition), but to the left side in Experiment 2B (left-positioned display condition). The display was a 21-in. LCD monitor with a 34° diagonal eccentricity (a location that is often used for a vehicle cockpit display; Wittmann et al., 2006). A dynamic visualization of an inaudible song through "splashes" of 48 green vertical bars was presented in the center of the display during the whole experiment, which was explained as a music display typically presented during driving. Participants were asked to imagine sitting inside a car, driving as in the United States for the right-positioned display condition, but as in Australia or Great Britain for the left-positioned display condition. The dynamic visualization was able to be seen in the peripheral visual field of participants and they were asked to keep the position during the whole experiment.

Results

Mean correct RTs and PEs per each participant, congruency condition, and response location were calculated. The congruency analysis was based only on the results of go trials. Using the same criteria as in Experiment 1, 2.7% trials for Experiments 2A and for 2B were excluded from analyses. The ANOVAs performed were similar to Experiment 1, except that display position was added as a between-subjects factor.

Response time. Besides the main effect of congruency, $F(1, 78) = 29.58$, $p < .001$, $\eta_p^2 = .275$, indicating an overall congruency effect of 10 ms relative to the wheel (see Table 1), the results also showed a three-way interaction of Congruency × Response Location × Display Position, $F(1, 78) = 5.30$, $p = .024$, $\eta_p^2 = .064$. This interaction reflects that the congruency effect was smaller for the response nearer to the infotainment display (6 ms) than for the one farther away (13.5 ms; see Figure 2, Exp2 panel), as predicted on the basis of coding of the responses relative to that display. Response location did not show a main effect, $F(1, 78) = 2.15$, $p < .146$, $\eta_p^2 = .027$. Moreover, the lack of a two-way interaction of Congruency × Response Location, $F < 1.0$, is consistent with the effects being of equivalent magnitude for the two display locations (8 ms larger for the left response with the right-positioned display compared with 7 ms larger for the right response with the left-positioned display).

Further analyses for each display position were performed. For the right-positioned display condition, besides main effect of congruency, $F(1, 39) = 14.72$, $p < .001$, $\eta_p^2 = .274$, the Congruency × Response Location interaction approached the .05 level, $F(1, 39) = 3.17$, $p = .083$, $\eta_p^2 = .075$. Separate ANOVAs for each response location showed that the 12-ms congruency effect for the left button was significant, $F(1, 39) = 24.31$, $p < .001$, $\eta_p^2 = .384$, whereas the 4-ms congruency effect for the right button was not, $F(1, 39) = 1.20$, $p = .281$, $\eta_p^2 = .030$. For the left-positioned display condition, the main effect of congruency was significant, $F(1, 39) = 15.40$, $p < .001$, $\eta_p^2 = .283$. The Congruency × Response Location interaction was not significant, $F(1, 39) = 2.19$, $p = .147$, $\eta_p^2 = .053$. Although the congruency effect was significant for both left and right responses, $Fs(1, 39) = 4.74$ and 14.43, $ps = .036$ and $< .001$, η_p^2s = .108 and .270, the difference was in the opposite direction (left < right) and of similar size (7 ms) compared with when the display was placed to the opposite side.

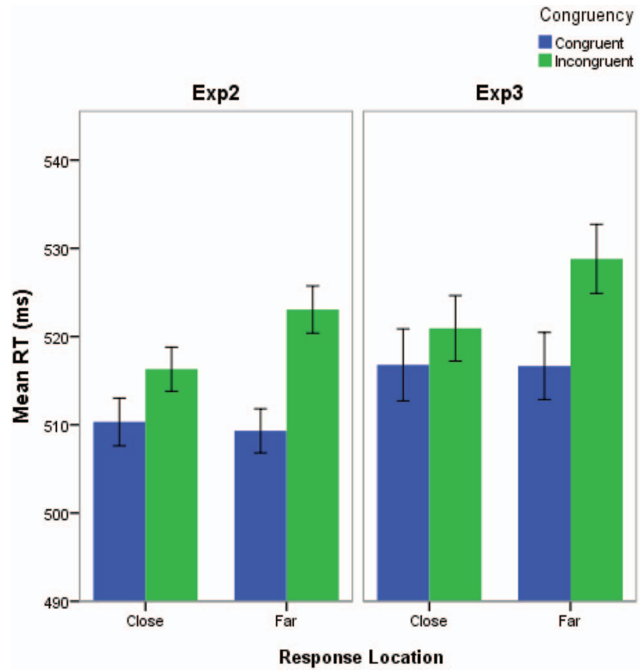

Figure 2. Mean RT as a function of congruency (congruent, incongruent), experiment (Exp2, Exp3), and response location (close, far). Error bars represent ±1 standard error of the mean calculated based on Cousineau's (2005) method for within-subject variables. Note: RT = reaction time; Exp2 = Experiment 2; Exp3 = Experiment 3. See the online article for the color version of this figure.

Response errors. PE showed no effect of congruency, response location, display position, or their interaction, $Fs < 1.0$ (see Table 1). As in Experiment 1, errors mainly involved pressing the assigned go button on no-go trials: PE showed no-go trials errors to be more frequent than go trials, $F(1, 78) = 16.425$, $p < .001$, $\eta_p^2 = 0.174$. Individual analyses for each display position showed that the PE was significantly larger on no-go trials than on go trials for right- and left-positioned display condition, $Fs(1, 39) = 12.01$ and 8.29, $ps = .001$ and .006, η_p^2s = .235 and .175.

Discussion

Experiment 2 investigated whether a right- or left-positioned display with dynamic visualization in a simulated driving cockpit would produce a larger Simon effect on the steering-wheel button that is far away from the display than the one that is close. Consistent with the hypothesis, the reduced Simon effects were obtained for the responses on the wheel side nearest to the display. That is, the Simon effect was larger for the left response with the right-positioned display and the right response with the left-positioned display than for the right response with the right-positioned display and the left response with the left-positioned display. That the relative size of the Simon effect for the two response locations switched across the two display positions reflects the agreement of wheel-based and infotainment-based spatial codes for the far button but not the near button.

Experiment 3

Although the three-way interaction was statistically reliable between the left- and right-positioned displays in Experiment 2, the effect was not very large and the comparison was between two groups of participants tested at different times of the semester. Therefore, we conducted Experiment 3 to replicate the results within a single experiment. Another change we made was to eliminate the neutral condition, which is most often not included in the social Simon go/no-go task paradigm (e.g., Dolk et al., 2013), with the thought that this might enhance coding the remaining tone locations as left and right, rather than as along a continuum. Otherwise, the experiment was similar to Experiment 2 and was expected to yield the same pattern of larger Simon effect for the response away from the infotainment display than for the one closer to it.

Method

Thirty students (22 male and eight female, with a mean age of 20 years; all but three were right-handed) participated in the right-positioned display condition, and 30 other students (18 male and 12 female, with a mean age of 20 years; all but two were right-handed) participated in the left-positioned display condition. Two additional participants from each condition were replaced on the basis of the same criteria as in the previous experiments. The sample size of 30 participants for each display position was based on a power analysis conducted with G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007), using an effect-size estimate based on the results of Experiment 2. More specifically, the calculated mean effect size ($f = 0.18$) for the response congruency effect on RT for each response location of the two display positions was input to estimate that this number of participants would yield an adequate power of 0.78.

The method for the respective display conditions was the same as for Experiments 2A and 2B, with the exception that the neutral trials were removed and the numbers of congruent and incongruent trials left unchanged. For each block, the participants first completed 12 practice trials (six go trials, six no-go trials), which were then followed by 240 experimental trials (half go trials, half no-go trials).

Results

Mean correct RTs and PEs as a function of congruency and response location were calculated for each participant. Applying the same exclusion criteria, 2.4% of trials were excluded for the right-positioned display condition and also the left-positioned display condition. ANOVAs of RT and PE similar to those of Experiment 2 were conducted.

Response time. The ANOVA showed a main effect of congruency, $F(1, 58) = 25.20$, $p < .001$, $\eta_p^2 = .303$, indicating a Simon effect of 8 ms (see Table 1), and a three-way interaction of Congruency × Response Location × Display Position at the .05 level, $F(1, 58) = 4.02$, $p = .0496$, $\eta_p^2 = .065$. Again, this interaction indicates a smaller Simon effect for responses nearer to the infotainment display (4.5 ms) than for the ones farther away (12 ms; see Figure 2, Exp3 panel), as predicted on the basis of coding of the responses relative to that display. For the response location, neither the main effect, $F < 1.0$, nor its interaction with congruency, $F(1, 58) = 1.19$, $p < .001$, $\eta_p^2 = .275$, were significant, consistent with Experiment 2.

Separate analyses were performed for each display position. For the right-positioned display condition, there was a main effect of congruency, $F(1, 29) = 14.25$, $p = .001$, $\eta_p^2 = .239$: Responses were faster on congruent (510 ms) than incongruent (518 ms) trials (see Table 1). The Congruency × Response location interaction was not significant, $F < 1.0$, indicating no difference between the 10- and 7-ms congruency effects observed, for the left and right responses, respectively. For the left-positioned display, responses were faster for the congruent trials (524 ms) than the incongruent trials (531 ms), as indicated by the main effect of congruency, $F(1, 29) = 11.07$, $p = .002$, $\eta_p^2 = .276$. The Congruency × Response Location interaction was significant, $F(1, 29) = 4.59$, $p = .041$, $\eta_p^2 = .137$, with the 14-ms congruency effect obtained for the right responses, $F(1, 29) = 11.14$, $p = .002$, $\eta_p^2 = .277$, being larger than the 2-ms effect obtained for the left responses, $F < 1.0$.

Response errors. No terms involving congruency or its interaction were significant, Fs < 1.46, but there was a main effect of response location, $F(1, 58) = 11.26$, $p = .001$, $\eta_p^2 = .163$: More errors occurred for the left response (1.3%) than the right response (0.5%). Also, more errors were made when the infotainment display was to the right (1.4%) rather than the left (0.5%), $F(1, 58) = 7.52$, $p = .008$, $\eta_p^2 = .115$. The go/no-go ANOVA showed a similar pattern as go trials: More error responses were obtained for left side (1.0%) than on the right side (0.6%), $F(1, 58) = 7.37$, $p = .009$, $\eta_p^2 = 0.113$; and there was also a main effect of display, $F(1, 58) = 6.11$, $p = .016$, $\eta_p^2 = .095$. The Go/No-Go × Response Location interaction was also significant, $F(1, 58) = 7.03$, $p = .010$, $\eta_p^2 = 0.108$, indicating the go/no-go difference was evident for the left responses, $F(1, 58) = 7.74$, $p = .007$, $\eta_p^2 = 0.118$, but not the right ones, $F < 1.0$.

Replication ANOVA of Experiments 2 and 3. To confirm the Simon effect across Experiments 2 and 3, we added replication (Experiment 2, Experiment 3) as a fourth factor (Winer, 1971, pp. 391–394), along with congruency, response location, and display position. For RT, the main effect of congruency, $F(1, 136) = 50.93$, $p < .001$, $\eta_p^2 = .272$, and the three-way interaction of Congruency × Response Location × Display Position, $F(1, 136) = 9.17$, $p = .003$, $\eta_p^2 = .063$, were significant. The evidence for the three-way interaction was confirmed to be positive, according to Raftery's (1995) classification, by calculation of a Bayes factor (Masson, 2011) of 0.12, which corresponds to a posterior probability of the alternative hypothesis of .89. No term involving replication was significant, Fs < 1.0, with the absence of four-way interaction being most crucial: Across Experiments 2 and 3, the Simon effect was a similar amount smaller for the response nearer to the infotainment display than for the one farther away. The PE ANOVA did not compromise this conclusion, as no term involving congruency was significant.

Discussion

Experiment 3 replicated the three-way interaction of Congruency × Response Location × Display Position for RT found in Experiment 2: A larger Simon effect was obtained for the responses performed by the steering-wheel button, which is far away from the display than by the one that close to it. Across the two display position conditions, the spatial coding of the far button on the steering wheel relative to the display was consistent, whereas the coding was not reliable for the button nearby. The lack of interaction with the replication factor indicates that the mean Simon effect was not impacted by the exclusion of the neutral trials.

General Discussion

Spatial Referential Coding

The horizontal dimension is particularly salient during driving, not only because the vehicle is always on the right or left side of the road, depending on the traffic rule, but also because the cockpit inside is filled with left–right positioned seats, a center-located infotainment display, left-seated driver, and so forth. Therefore, multiple spatial reference frames are provided inside the vehicle cockpit. In the present study, we demonstrated spatial coding relative to two reference frames, the wheel on which the left and right hands were positioned and a simulated infotainment system located to the left or right of the wheel.

The Simon effect is typically negligible in go/no-go tasks when there is no person or salient object to provide a reference frame for coding the response as left or right (e.g., Hommel, 1996). However, the steering wheel with the driver's hands positioned on it is a relatively salient object that could serve as a reference frame. We provided evidence that such was the case in Experiment 1, which showed an 11.5-ms Simon effect relative to whether the button-press response for the trial block was the left or right one. Whether this Simon effect is due to the buttons on the wheel, the requirement to place both hands on the wheel, or having the thumb of the nonresponding hand on an active response button cannot be determined from the present study. But results reported by Hommel (1996) and Ivanoff and Klein (2001) are consistent with the possibility that placing the nonresponding hand on an active response button is crucial. In Hommel's Experiment 4, a 16-ms correspondence effect was obtained when participants performed a simple-reaction task with a second, nonresponding finger from the same hand as the responding finger placed on a response key. Ivanoff and Klein also reported a significant Simon effect of 7 ms for a simple-reaction task requiring responses with an index finger, but only when the other index finger was placed on a task-irrelevant response key. Finally, Reeve and Proctor (1988) found in a spatial two-choice reaction task that RT was increased when nonresponse fingers were placed on active response keys rather than on immovable blocks.

Across Experiments 2A and 2B, the position of the infotainment display interacted such that the Simon effect was smaller for the response nearer the display than for the one farther away. When the display was positioned to the right side of the steering wheel in Experiment 2A, simulating its placement in a right-hand traffic vehicle, a significant Simon effect was observed for the left response but not the right one. When the display position was to the left side of the steering wheel in Experiment 2B, simulating its placement in a left-hand traffic vehicle, significant Simon effects were obtained for both responses, but the effect tended to be smaller for the left response than for the right one. This influence of the infotainment display on the Simon effect was small numerically (7.5 ms), but it was replicated in Experiment 3. These results imply that the button responses were coded relative to the infotainment display, which reduced the Simon effect for the response nearest to the display.

In prior go/no-go tasks showing an influence of a coactor or reference object (e.g., Dolk et al., 2013; Sebanz et al., 2003), the coactor or object was positioned to the opposite side of the active response. This arrangement essentially completes the task's left and right response configuration (e.g., a person pressing the key that is to the left of the participant's response key essentially makes the response selection a left or right choice). In the present case, the positioning of the buttons and hands on the wheel completed the response configuration (i.e., there were left and right responses, even though only one was to be pressed), and the infotainment display was extraneous to this configuration. Nevertheless, the display position affected the coding of the left and right button presses, providing evidence that spatial information outside of the primary response configuration can impact performance. Although, as noted, the absolute size of the effect of the infotainment display was small, it was not small considering that the task was go/no-go, which does not explicitly requiring response selection and therefore yields at most small Simon effects. This is apparent in that the wheel-based, left–right Simon effect averaged about 10 ms across the three experiments, compared with about 50 ms for auditory Simon effects in choice-reaction tasks (Simon, 1990). When viewed in this manner, the influence of the irrelevant infotainment display on performance was about .75 that of the relevant left–right response distinction.

Although the responses were coded relative to the infotainment display, they also were coded relative to the wheel-based frame. Experiments 2 and 3 also showed a main effect of congruency, indicating that, with the influence of the infotainment display neutralized, there was still a Simon effect of 10 and 8 ms, respectively. These values are similar to the 11.5-ms effect obtained in Experiment 1 without an infotainment display, implying that response activation associated with the wheel-based frame was similar across experiments, with the activation associated with the infotainment display have a separate effect, either additive or subtractive, depending on the congruence of the two sources of activation.

Implications for Driving

Inside the vehicle, the driver commonly responds with a specific spatially defined button on the steering wheel to one auditory stimulus value (e.g., press the phone button on steering wheel to answer phone call when a ringtone is heard), which is similar to a go/no-go Simon task. The results of the current study indicate that the appropriate steering-wheel button can be operated faster if it is spatially compatible with the acoustic stimulus than if it is not, but this compatibility can be influenced by the spatial coding provided by other salient spatial reference frames.

With the steering wheel located in the center of the desk in the present study, and the participant center-aligned with the wheel, the spatial referential coding conflict imposed on the close response in Experiments 2 and 3 may have been weaker than that in a real driving cockpit. In a cockpit of a right-hand traffic vehicle, both the steering wheel and driver are left-located, which adds another spatial conflict with the coding of the right-hand response relative to the wheel. The passenger seat on the right provides extra potential spatial coding conflict for the right response, as does a passenger seated on the right side of the driver. Therefore, instead of a correspondence benefit for a right-located stimulus with a right-hand button-press response in a real driving environment, there may be a cost as a consequence of the multiple irrelevant spatial referential codes indicating left (Roswarski & Proctor, 1996).

The infotainment display implemented in Experiments 2 and 3 was not merely an object; it presented a dynamic visualization of green vertical bars in the center of the display to simulate the display information, which typically seen on the infotainment display during driving. No doubt this kind of event would attract the participant's attention and therefore provide a spatial frame of reference to code the response, consistent with the conclusion of Dolk et al. (2013) that it is the dynamic aspect of an irrelevant object that provides a basis for referential response coding. Our three experiments provide proof of concept that the pushbutton responses are coded as left and right with respect not only to the wheel basis but also to a salient object like the infotainment display.

It should also be noted that the operation of the button in this study was simple, as only one button was relevant during any trial block. Lately, multiple buttons related to a single function have been proposed (Mossey, 2013), or have come to be used, in steering-wheel button design, such as one button for increasing volume and another for decreasing volume. Therefore, a two-choice or multiple-choice task is involved in the operation of steering-wheel buttons. The spatial arrangement within the group of buttons on one side of the wheel provides an additional reference frame relevant to the response coding (e.g., Murata & Moriwaka, 2007), which may affect the left–right spatial coding of the responses. This issue can be investigated in future research that measures the performance differences between and within button groups.

Besides, unlike in a driving scenario, pressing the steering-wheel button had no effect on the infotainment display. Because anticipation of response effects is crucial in action selection (e.g., Janczyk, Yamaguchi, Proctor, & Pfister, 2015), the compatibility of the response-effect relations may influence the button responses. Links between the buttons and the infotainment display also may introduce a contribution of proximity compatibility (Wickens & Carswell, 1995), that is, the button close to the display may be more strongly associated with its operation. The interaction among S–R congruency, response-effect compatibility, and proximity compatibility needs to be examined with tasks linking the buttons to the infotainment display.

Because driving itself is a spatial perceptual-motor task, it may impact the spatial information processing that occurs within the cockpit. It remains to be determined whether the tendency of a faster response with the left-side steering-wheel button of a right-traffic vehicle will generalize to the driving context. This issue can be evaluated by conducting an experiment similar to the present ones within a simulated driving scenario. Although a static steering wheel without maneuvers was used in the current study, it presented a proof of concept for the operation of the buttons when the steering wheel is in its neutral position, in which a driver would be most likely to press the buttons. Thus, the impact from the rotation of the steering wheel should not be a big concern. Because the same spatial relations between the left and right steering-wheel buttons and the infotainment display exist in a driving scenario, similar spatial congruency effects may be expected to occur. Simulated driving studies have found spatial compatibility effects in the range of hundreds of milliseconds (e.g., Liu & Jhuang, 2012), suggesting that the effects may even be much larger in the driving scenario. However, there is also a possibility that interactions between the tasks of controlling the vehicle and operating the buttons may diminish the role of spatial correspondence (Yamaguchi & Proctor, 2006).

Conclusion

The present experiments confirm that a salient visual object, in this case, the simulated infotainment display, can affect go/no-go Simon task performance in much the same way that a coactor does. They also show that this coding of response position relative to the object can occur in addition to coding relative to a left versus right response frame. With regard to the driving cockpit, the results provide evidence that the spatial compatibility of a steering wheel's left and right button responses can be influenced by the multiple spatial reference frames within the cockpit. As demonstrated, the response spatial coding was impacted by a task-irrelevant simulated infotainment display that was outside of the primary wheel-based response configuration. Specifically, an infotainment display positioned to the right of the steering wheel, as in the United States, can induce spatial coding conflicts to the response made with the steering wheel's right button, decreasing the benefit of spatial correspondence. Hence, a practical suggestion for the layout of the steering-wheel buttons is to put the safety and driving-related features, which require the fastest responses, on the left side of the steering wheel.

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