Factors Affecting Speed and Accuracy of Response Selection in Operational Environments

Robert W. Proctor & Motonori Yamaguchi

Department of Psychological Sciences, Purdue University, West Lafayette

Abstract

Models of human information processing have been useful tools for analyzing and predicting human performance. A typical model breaks task performance into three broad processes: stimulus encoding, response selection, and motor execution. The response-selection process is the most critical in determining the speed and accuracy of performance in a complex operational environment. We describe research conducted for the Multidisciplinary University Research Initiative project, *Training Knowledge and Skills for the Networked Battlefield,* that investigates factors that affect speed and accuracy of response selection. Implications of the research for interface designs and training of operational skills are discussed.

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Factors Affecting Speed and Accuracy of Response Selection in Operational Environments

The research described in our paper was conducted for the Multidisciplinary University Research Initiative (MURI) project, *Training Knowledge and Skills for the Networked Battlefield*, supported by the U.S. Army Research Office. This MURI project is a five-year grant, started in 2005, for which Alice Healy and Lyle Bourne of the University of Colorado, Boulder, are the principal investigators. The main objective of the project is "to construct a theoretical and empirical framework that can account for and make accurate predictions about the effectiveness of different training methods" (http://psych.colorado.edu/~ahealy/MuriFrame.htm). The project adopts an integrated approach that involves (a) experimental investigations of components and principles for training of individuals and teams, (b) development of a taxonomy for training programs, and (c) ACT-R and IMPRINT modeling of training efficiency. Our part of the project focuses on the basic components of skill training, which are of primary interest for both human interface design and training of perceptual-motor skills.

Since the rapid growth of cognitive theories in the mid 1950s, human performance has been analyzed from an information-processing perspective (Proctor & Vu, 2006b), which decomposes task performance into distinct processing components (e.g., Card, Moran, & Newell, 1983). Information-processing models typically consist of three major subsystems – stimulus encoding, response selection, and response execution (see Figure 1) – of which the most critical component in determining the speed and accuracy of performance is that of response selection (Welford, 1960). Consequently, factors that affect response-selection processes have been of theoretical and practical concern. They include, for example, the number of alternative choices (Hick, 1952), the interval between tasks (Smith, 1967), cognitive load (Baddeley, 1998), task sequence (Monsell, 2003), and compatibility between stimuli and responses (Fitts & Seeger, 1953).

Among those factors, the compatibility between stimuli and responses has been recognized as one of the most important in designing operational systems to provide optimal task performance. In basic psychological research, the effect of compatibility is termed *stimulus-response compatibility* (SRC; Proctor & Vu, 2006a), whereas in applied human factors research it is often called *display-control compatibility* (Andre & Wickens, 1990). The SRC effect occurs when responses are mapped to stimuli for which there are some corresponding attributes, or dimensional overlap. These stimulus and response attributes may be their spatial locations (e.g., a signal displayed on the left side of the monitor and a response device placed on the left of the operator), or symbology of displays used to indicate controlling actions (e.g., arrow pointing to the left as a signal to turn a vehicle to the left). When stimuli are mapped to the corresponding responses, the stimulus-response (S-R) mapping is called *compatible,* whereas when they are mapped to noncorresponding responses the mapping is called *incompatible* (see Figure 2a).

The SRC effect is often attributed to population stereotypes (Fitts & Seeger, 1953) or long-term associations (Barber, & O'Leary, 1997) acquired through experience. A traditional description of the SRC effect is that stimuli are more easily translated into responses when they correspond than when they do not. The advantage for compatible stimulus and response sets remains intact after several days of practice with the task (Dutta & Proctor, 1992; Fitts & Seeger, 1953), and the SRC effect is robust in a variety of task settings (Proctor & Vu, 2006a). Nevertheless, in recent studies we identified several task conditions in which the advantage of the compatible mapping is reduced or eliminated. In the following sections, we describe several lines of research conducted for the MURI project that include such conditions.

SRC Effect in Mixed-Mapping Task

In the first line of research, we examined the SRC effect in a flight simulator (Yamaguchi & Proctor, 2006, 2007). In one study, participants monitored the primary flight display and banked the aircraft by turning the yoke to the left or right according to the location of a signal presented on the display. They were to bank the aircraft in the direction corresponding to the signal location in one condition and in the direction opposite the signal location in another condition. That is, participants always responded compatibly or incompatibly to the signal locations depending on the mapping condition. Response times (RTs) and percentage errors (PEs) for the two conditions showed a relatively large SRC effect. Of more interest, in another condition, participants were required to choose on each trial whether to bank the aircraft compatibly or incompatibly to the signal location on the basis of its color: When the signal was green, participants were to bank the aircraft toward the signal location, but when the signal was red, they were to bank away from the signal location. Thus, the compatible and incompatible mappings were intermixed in a single task condition.

Responses were generally slower and less accurate when the two mappings were mixed than when they were not, indicating a *mixing cost*. More important, the cost of mixing was larger for trials with compatible mapping than those with incompatible mapping, which reduced the SRC effect. Moreover, when the yoke-turn responses were replaced with presses of buttons on the left and right handles of the flight yoke, the SRC effect with mixed mappings was completely eliminated (see Figure 3). In a follow-up study (Yamaguchi & Proctor, 2008a), we observed that the elimination of the SRC effect in a mixed-mapping task was stable with the button-press responses but with the yoke-turn responses seemed to depend on the participants' strategy. Namely, with yoke turns, the SRC effect appeared when responses were made quickly but less accurately, whereas it was eliminated when responses were made slowly but more accurately;

thus, this observation seems to reflect speed-accuracy tradeoffs. A possibility is that modes of responding differently affect participants' strategy, but it also seems possible that the observation is due to the fact that these response modes allow different types of response preparation. In fact, a previous study suggested that preparatory states can affect the reduction/elimination of the SRC effect in a mixed-mapping task (De Jong, 1995).

We also conducted a series of experiments using a mixed-mapping task with four alternative responses (Proctor & Vu, 2008), rather than only two alternatives as in the studies discussed previously. Stimuli were presented on the left or right of the screen in green or red, with color indicating whether the mapping of stimulus locations to responses was compatible or incompatible. Two keys were operated by the middle and index fingers of the left hand for one mapping, and another two keys were operated by the index and middle fingers of the right hand for the other mapping. Thus, while participants were required to select the appropriate mapping on each trial, each response was assigned to only a single mapping. In this case, the SRC effect was neither eliminated nor reduced by mixing the two mappings (see Figure 4), most likely because the mapping of stimulus location to each response was consistent rather than variable. Though it is still left to future research to determine exactly which environmental manipulations can influence the pattern of SRC effects in mixed-mapping tasks, both the two- and four-alternative choice tasks suggest that the nature of responses modulates the SRC effect in mixed-mapping tasks.

Transfer of Learning: 1. Sensory Modality

Robustness of the SRC effect is also implied by the fact that responses are typically faster and more accurate when a "task-irrelevant" stimulus attribute overlaps with a response attribute. The SRC effect on the basis of a task-irrelevant stimulus dimension is called the *Simon effect*, and the task that produces this effect is called the Simon task (Lu, & Proctor, 1995; Simon, 1990). In a typical Simon task, participants are asked to make a left or right keypress in response to the color of the stimulus that appears on the left or right of the screen (see Figure 2b). Even though participants are instructed to ignore the spatial dimension of stimuli, responses are faster and more accurate when they correspond to the spatial stimulus attributes than when they do not, yielding the Simon effect. Although the Simon effect is also known to persist through several days of practice for the task (e.g., Proctor & Lu, 1999; Simon, Craft, & Webster, 1973), another line of research we have conducted for the MURI project shows that the Simon effect can be reduced, eliminated, or even reversed in certain task contexts.

In the first study of this type, Proctor and Lu (1999) had participants complete 930 trials of a two-choice reaction task with the spatially incompatible mapping over three consecutive days and then perform the Simon task on the fourth day. For that task, the typical Simon effect was reversed such that responses to noncorresponding stimuli were faster than responses to corresponding stimuli. Subsequently, Tagliabue, Zorzi, Umiltà, and Bassignani (2000) reported elimination of the Simon effect after participants had performed only 72 trials of the incompatible-mapping practice task.

Instead of using visual stimuli for the two tasks, Vu, Proctor, and Urcuioli (2003) used auditory stimuli for both and found that transfer of the incompatible mapping to the Simon task did not occur. We followed up this study, assessing whether the lack of transfer effect was due to the nature of the auditory stimuli or insufficient practice (Proctor, Yamaguchi, & Vu, 2007). Groups of participants performed 84, 300, or 600 trials of the incompatible-mapping task and then transferred to the Simon task, with both tasks using auditory stimuli. The Simon effect was significantly reduced after 300 and 600 practice trials, but not after 84 practice trials, compared to a control group that performed only the Simon task (see Figure 5). These results indicate that auditory stimuli produce a stronger tendency to make spatially corresponding responses than visual stimuli and more extended practice is required for transfer of learning with auditory stimuli.

In an unpublished study, we also had participants perform the same amounts of practice with visual stimuli and transfer to the Simon task with auditory stimuli. In this case, there was no transfer effect even after 600 or 1,200 practice trials. In contrast, in Vu et al.'s (2003) study (see also Tagliabue, Zorzi, & Umiltà, 2002), there was a significant transfer effect when participants practiced with auditory stimuli for 84 trials and then transferred to the visual Simon task, indicating an asymmetric pattern of transfer between visual and auditory stimuli. The studies suggested collectively that the amount of practice strengthens the transfer of learning, but there is specificity of transfer that is difficult to overcome even with extended practice.

These results led us to investigate factors responsible for the specificity of transfer, which is also of particular interest in the study of training principles in the MURI project (Healy, Wohldmann, Parker, & Bourne, 2005; Healy, Wohldmann, Sutton, & Bourne, 2006). We reported the first experiment in our transfer study with auditory stimuli described above (Proctor et al., 2007), which showed that the transfer effect was specific to the practiced spatial dimension (see also Vu, 2007). When participants performed a task with stimuli and responses arranged horizontally, there was a significant transfer effect when the stimuli and responses in the subsequent task were also arranged horizontally but little transfer effect when they were arranged vertically. The same was true when participants practiced with vertically arranged stimuli and responses; transfer was significant when the subsequent task involved vertically arranged stimuli and responses but not when it involved horizontally arranged ones (see Figure 6). In other words, there were transfer effects within the same spatial dimension but not between different spatial dimensions. There was also evidence of between-dimension transfer for visual stimuli, though, when extended practice was provided (Vu, 2007). These outcomes suggest that the transfer effect with short practice depends on S-R associations that are specific to the practiced spatial dimension, whereas extended practice not only strengthens the association but also can lead to acquisition of an abstract rule (i.e., “respond opposite”) for S-R transformation.

Transfer of Learning: 2. Stimulus Codes

It has been acknowledged that the SRC and Simon effects depend on how stimulus information and response information are encoded rather than their physical attributes (e.g., Proctor & Cho, 2006). The notion of stimulus and response codes is implicated because SRC and Simon effects can occur on the basis of S-R correspondence that emerge on their salient feature dimensions (Proctor & Reeve, 1985), spatial locations of stimulus and response keys rather than responding hands (Wallace, 1971), and as a consequence of responding (e.g., task goal; Hommel, 1993). Spatial information can be conveyed by symbols (e.g., arrows pointing to a direction) or words (e.g., ‘LEFT’ or ‘RIGHT’), as well as by physical stimulus location (e.g., a circle on the left or right of the display). These different manners of conveying spatial information also yield the Simon effect (Lu & Proctor, 2001). Some models attribute the SRC effect to spatial codes of a general nature that are independent of specific stimuli or responses (e.g., Zhang, Zhang, & Kornblum, 1999). However, it is also possible that the SRC effect depends on spatial codes that are specific to the types of stimuli and responses. This issue can be examined using the transfer paradigm by varying stimuli used in the practice and transfer sessions. Thus, in the next series of experiments, we examined the specificity of transfer in terms of the types of stimulus code that effects response-selection processes (Proctor, Zhang, Yamaguchi, & Vu, 2008).

First, we tested whether the transfer effect could be observed for three types of stimuli, physical locations (circles on the left or right of the display), arrow directions (pointing to the left or right), and location words ('LEFT' or 'RIGHT'). A significant transfer effect occurred in the Simon task after 84 practice trials of the incompatible-mapping task for physical location and arrow directions but not for location words. Subsequently, we varied the stimuli used in the practice and transfer sessions and found that nearly perfect transfer occurred between physical locations and arrow directions, indicating that they shared the same stimulus codes. However, there was no significant transfer effect between location words and physical locations or arrow directions. Therefore, the results are indicative of two types of stimulus codes; *visuo-spatial* for physical locations and arrow directions, and *verbo-spatial* for location words. The lack of transfer effect from physical locations and arrow directions to location words is consistent with the distinction between visuo- and verbo-spatial codes. Nevertheless, the lack of transfer from location words to physical locations or arrow directions could have been due to the fact that the amount of practice was simply insufficient to yield a significant transfer effect, because practice with location words did not show transfer within the same stimulus codes.

As in the case of auditory stimuli, therefore, we tested whether extended practice could lead to transfer of the incompatible mapping for location words (Proctor, Yamaguchi, Zhang, & Vu, 2008). The amounts of practice were 84, 300, 600 trials with location words, which were compared to the control group who did not perform the practice session. The results were consistent with those for auditory stimuli: Significant transfer appeared after 300 and 600 practice trials, whereas there was no transfer after 84 trials. Further, we examined whether extended practice with location words could produce a transfer effect to physical locations or arrow directions. The results suggested that there was significant transfer from location words to arrow directions but not to physical locations. In fact, there was some evidence in the previous study (Proctor et al., 2008) that arrow stimuli have both visuo- and verbo-spatial characteristics, probably due to the fact that they have both perceptual and semantic (symbolic) spatial attributes. Similarly, when participants were given extended practice with arrow directions and then transferred to the Simon task with location words, there was a clear tendency of transfer effect. In contrast, even when they had extended practice with physical locations, little transfer to location words was evident.

In summary, we observed that there was code-specific transfer of the incompatible mapping to the Simon task when stimuli varied between the practice and transfer sessions. In particular, the results of our studies are consistent with the distinction between visuo-spatial and verbo-spatial codes. Transfer can occur with a relatively small amount of practice for visuo-spatial codes, whereas extended practice is required for verbo-spatial codes. Interestingly, arrow stimuli seem to involve both types of spatial codes. Hence, transfer of learning depends on the type of stimulus codes rather than on a general spatial code.

Transfer of Learning: 3. Response Codes

So far, we have only considered the influences of stimulus domain on transfer of learning. As discussed in the section on mixed-mapping tasks, however, response domain is also an important factor that affects response selection. Consequently, we examined the influences of this domain on transfer of the incompatible mapping (Yamaguchi & Proctor, 2008b).

Though simply called “response,” it is a complex composite of several different factors. For instance, the response device used in performing a task provides the immediate perceptual attributes of responding. Also, a specific action (response mode) required for a task provides the immediate motor components of responding. Moreover, there is evidence reported in the literature that the consequence of an action, rather than the action itself, provides the immediate conceptual basis of responding (e.g., Hommel, 1993). Hence, influences of these factors have to be dissociated and examined separately. By using the transfer paradigm, the main effort was toward which of these factors would be central to constitute response codes.

A difficulty of dissociating the influence of response device from that of response mode is that changing one usually alters the other. For instance, though the same computer operation can be performed by using a computer mouse or a touchpad, switching from one device to the other alters the actual actions taken in performing the task, thus confounding two different factors. To exclude the problem, we used two types of response devices that are designed to make keypresses, one with a standard keyboard and the other with the response box for psychological research. The task used physical-location stimuli similar to our preceding experiments for both practice and transfer sessions. The results indicated that nearly perfect transfer was achieved when switching response devices between the two sessions, excluding this factor from our consideration.

Having excluded the influence of response device, we varied response modes between the practice and transfer sessions. Two types of response modes used in our second experiment were keypresses on a standard keyboard and deflections of a joystick. This factor exerted a significant influence on transfer of the incompatible mapping. That is, the transfer effect was reduced when response modes varied between the practice and transfer sessions compared to when they were held constant, indicating the importance of response mode (see Figure 7). Some researchers suggest, however, that the SRC effect depends on the correspondence of the environmental stimuli with one’s intentions (Hommel, Müsseler, Aschersleben, & Prinz, 2001). They argue that such intentions are not so much as to what actions are taken but as to what effects people want to produce in the environment by taking those actions. Thus, it is the consequences of actions rather than the actions themselves that are central to constitute responses. In the psychological literature, the consequence of responding is called an *action effect*. For example, an action effect can be a light turned on when a switch is pressed. In a task where pressing a left key turned on a light placed on the right and pressing a right key turned on a light placed on the left; that is, the response location and the side of action effect were incompatible, the Simon effect occurred on the basis of spatial correspondence between locations of stimuli and action effects, rather than between locations of stimuli and response locations, when instructions emphasized the former correspondence (Hommel, 1993).

Therefore, in a third experiment, we assessed the influence of action effect in which the two response modes used in the second experiment were employed. The question was whether participants would ignore a change of response mode when the action effects were identical for different response modes. We used a condition in which a left keypress or deflection of the joystick triggered presentation of a filled square on the left side of the screen and a right keypress or deflection triggered presentation of a filled square on the right side. Though the location or direction of response and its effect were compatible in our task, the location of action effect should have a stronger influence than that of response location/direction in performing the task if the action effect is the critical factor. If such is the case, a nearly perfect transfer effect would be observed even when response modes were varied between the practice and transfer sessions. The results showed that there were 10-20 ms reductions in the Simon effect for all conditions, compared to those conditions in Experiment 2 where action effects were absent. However, there was also a significant reduction of the transfer effect when response modes were varied, especially when participants practiced with the joystick and transferred to the keyboard, compared to when they practiced with the keyboard (see Figure 8).

The results of the three experiments described in this section collectively point to the importance of response mode in transfer of newly acquired S-R associations. The nearly perfect transfer between the two response devices suggests that the transfer effect is not always reduced by a change in task context. In contrast, it depends on manipulations of environmental factors that are critical to represent performance variables (i.e., stimulus and response). Although these experiments should not be taken to indicate that the response device and action effect have no influence on response-selection processes, the specificity of transfer to the trained response mode suggests that construction of a response representation is centered at the actions that are taken to perform the task.

Implications for Interface Design and Skill Training

We have described several lines of research conducted for the MURI project that investigate factors affecting response-selection processes in operational environments, with particular emphasis on basic perceptual-motor skill components. It is widely acknowledged that response selection is the central cognitive process that influences the speed and accuracy of task performance and benefits most from training. Thus, our research provides several results that are suggestive of both designing human interfaces and training efficiency of perceptual-motor skills.

The most important take-home message is, of course, that human interfaces should be designed in a way that maximizes the compatibility of information presentation and actions that are taken in response to the information, if the operational environment is to be made more efficient. This was the starting point of our research project. In the first section, we discussed that mixing the compatible mapping with the incompatible mapping increases both RT and PE, which we called mixing costs. Moreover, the advantage of the compatible mapping is significantly reduced or even eliminated in that condition. It is thus important that great care be taken to eliminate any display-control incompatibility in operational systems. Also, our study suggested that response conflict is a primary cause of the reduction/elimination of the advantage of the compatible mapping. Thus, if it is not possible to exclude incompatibility, operational environments should be carefully designed to separate compatible and incompatible operations to avoid their conflicts. In this way, the advantage of display-control compatibility can be retained in a complex operational environment.

Other experiments showed that the task-irrelevant SRC effect (Simon effect) is robust in a variety of task conditions, across different sensory modalities, stimulus codes and dimensions, and response modes. They indicate that compatibility not only in task-relevant display-control relationships but also in task-irrelevant ones should be considered. Neglect of these factors can lead to human-induced errors, which are often the leading cause of incidents and accidents. Furthermore, these studies suggest that experience with an incompatible task setting can continue to influence performance of subsequent tasks, eliminating or even reversing the compatibility relationships. Surprisingly, the amount of experience does not have to be large to exert its inadvertent influence, especially when these tasks are similar in their operations. This is another reason why the display-control compatibility should be carefully examined in designing human interfaces and task environments.

In addition to the issue of compatibility in interface design, our research suggests several factors that are important for transfer of learning in perceptual-motor skills. In general, transfer can occur with a small amount of practice. However, such transfer is specific to several operational factors, such as sensory modality, stimulus code, and response mode. This is in conformity with the principle of training specificity proposed by Healy, Bourne, and colleagues (e.g., Healy, Wohldmann, Parker, & Bourne, 2005; Healy, Wohldmann, Sutton, & Bourne, 2006). Although generality can be obtained with extended amounts of practice, it is not always the case. Some operational factors have stronger influences on response selection than others so that extended practice cannot overcome the effect, and some cause slow learning processes. Because unique factors of these types exist for different operation skills, it is difficult to generate a general list of such factors. Nevertheless, it is suggested that identification of unique factors would benefit training programs to gain efficiency, by either excluding them or developing an intensive battery to train on them.

A general recommendation for skill training derived from the present research is that the context of training should approximate the actual task environments as closely as possible. For instance, although use of virtual reality (VR) and high-fidelity simulator technologies can aid some aspects of training, such technologies are, at the current state of arts, limited in mimicking the real contexts. As a consequence, they probably can be used most efficiently to familiarize trainees with specific operations. However, in contrast to the recent popularity of these technologies, a high level of expertise is likely to be achieved more effectively by performing the operations in a simulation that takes place in a physical environment closely related to the actual conditions. Because our research is not specifically designed to investigate this issue, it remains a speculation that future research will need to settle.

References

Andre, A. D. & Wickens, C. D. (1990). *Display-control compatibility in the cockpit: Guidelines for display layout analysis*. Tech. Rep. University of Illinois Aviation Research Laboratory: Savoy, IL.

Baddeley, A. (1998). Recent developments in working memory. *Current Opinion in Neurobiology*, *8*, 234-238.

Barber, P., & O'Leary, M. (1997). The relevance of salience: Towards an activation account of irrelevant stimulus-response compatibility effects. In B. Hommel & W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility* (pp. 135-172). Amsterdam: North-Holland.

Card, S. K., Moran, T. P., & Newell, A. (1983). *The psychology of human-computer interaction*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

De Jong, R. (1995). Strategical determinants of compatibility effects with task uncertainty. *Acta Psychologica*, *88*, 187-207.

Dutta, A., & Proctor, R. W. (1992). Persistence of stimulus-response compatibility effect with extended practice. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*, 801-809.

Fitts, P. M., & Seeger, C. M. (1953). S-R compatibility: Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology*, *46*, 199-210.

Healy, A. F., Wohldmann, E. L., Parker, J. T., & Bourne, L. E., Jr. (2005). Skill training, retention, and transfer: The effects of a concurrent secondary task. Memory & Cognition, 33, 1457-1471.

Healy, A. F., Wohldmann, E. L., Sutton, E. M., & Bourne, L. E., Jr. (2006). Specificity effects in training and transfer of speeded responses. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*, 534-546.

Hick, W. E. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology*, *4*, 11-26.

Hommel, B. (1993). Inverting the Simon effect by intention. *Psychological Research*, *55*, 270-279.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for peception and action planning. *Behavioral and Brain Science, 24*, 849-937.

Lu, C.-H., & Proctor, R. W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin & Review, 2*, 174-207.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*, 134-140).

Proctor, R. W., & Cho, Y. S. (2006). Polarity correspondence: A general principle for performance of speeded binary classification task. *Psychological Bulletin*, *132*, 416-442.

Proctor, R. W., & Lu, C.-H. (1999). Processing irrelevant location information: Practice and transfer effects in choice-reaction tasks. *Memory & Cognition, 27*, 63-77.

Proctor, R. W., & Reeve, T. G. (1985). Compatibility effects in the assignment of symbolic stimuli to discrete finger responses. *Journal of Experimental Psychology: Human Perception and Performance*, *11*, 623-639.

Proctor, R. W., & Vu, K.-P. L. (2006a). *Stimulus-response compatibility principles: Data, theory, and application*. Boca Raton, FL: CRC Press.

Proctor, R. W., & Vu, K.-P. L. (2006b). The cognitive revolution at age 50: Has the promise of the human information-processing approach been fulfilled? *International Journal of Human-Computer Interaction*, *21*, 253-284.

Proctor, R. W., & Vu, K.-P. L. (2008). Stimulus-response compatibility for mixed mappings and tasks with unique responses. *Manuscript submitted for publication*.

Proctor, R. W., Yamaguchi, M., & Vu, K.-P. L. (2007). Transfer of noncorresponding spatial associations to the auditory Simon task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33,* 245-253.

Proctor, R. W., Yamaguchi, M., Zhang, Y., & Vu, K.-P. L. (2008). Transfer of noncorresponding spatial associations between visuo- and verbo-spatial codes with extended practice. *Manuscript in preparation*.

Proctor, R. W., Zhang, Y., Yamaguchi, M., & Vu, K.-P. L. (2008). Modulation of spatial correspondence effects by learned incompatible stimulus-response associations: Transfer within and between different visual stimulus modes. *Manuscript submitted for publication.*

Simon, J. R. (1990). The effects of an irrelevant directional cue on human information processing. In R. W. Proctor & T. G. Reeve (Eds.), *Stimulus-response compatibility: An integrated perspective* (pp. 31-86). Amsterdam: North-Holland.

Simon, J. R., Craft, J. L., & Webster, J. B. (1973). Reactions toward the stimulus source: Analysis of correct responses and errors over a five-day period. *Journal of Experimental Psychology*. *101*, 175-178.

Smith, M. C. (1967). Theories of the psychological refractory period. *Psychological Bulletin*, *67*, 202-213.

Tagliabue, M., Zorzi, M., & Umiltà, C. (2002). Cross-modal re-mapping influences the Simon effect. *Memory & Cognition, 30,* 18-23.

Tagliabue, M., Zorzi, M., Umiltà, C., & Bassignani, F. (2000). The role of LTM links and STM links in the Simon effect. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 648-670.

Vu, K.-P. L. (2007). Influences on the Simon effect of prior practice with spatially incompatible mappings: Transfer within and between horizontal and vertical dimensions. *Memory & Cognition*, *35*, 1463-1471

Vu, K.-P. L., Proctor, R. W., & Urcuioli, P. (2003). Effects of practice with an incompatible location-relevant mapping on the Simon effect in a transfer task. *Memory & Cognition, 31*, 1146-1152.

Wallace, R. J. (1971). S-R compatibility and the idea of a response code. *Journal of Experimental Psychology*, *88*, 354-360.

Welford, A. T. (1960). The measurement of sensory-motor performance: Survey and reappraisal of twelve years' progress. *Ergonomics*, *3*, 189-230.

Yamaguchi, M., & Proctor, R. W. (2006). Stimulus-response compatibility with pure and mixed mappings in a flight task environment. *Journal of Experimental Psychology: Applied*, *12*, 207-222.

Yamaguchi, M., & Proctor, R. W. (2007). Effect of display format on attitude maintenance performance. In R. Jensen (Ed.), *Proceedings of the 14th International Symposium of Aviation Psychology* (pp. 776-781). April 23-26, 2007. Dayton, OH: Write State University.

Yamaguchi, M., & Proctor, R. W. (2008a). Influences of continuous and discrete stimulus and response sets on stimulus-response compatibility effects with pure and mixed mappings. *Manuscript submitted for publication*.

Yamaguchi, M., & Proctor, R. W. (2008b). Specificity and generality of transfer effect: Influence of response attributes and attention weights. *Manuscript in preparation*.

Zhang, H., Zhang, J., & Kornblum, S. (1999). A parallel distributed processing model of stimulus-stimulus and stimulus-response compatibility. *Cognitive Psychology, 38,* 386-432.

Figure Captions

Figure 1. An illustration of three-stage model of human information-processing and examples of operational factors that affect the processing stages.

Figure 2. Examples of the stimulus-response (S-R) mappings for the SRC task and the Simon task: For the SRC task (a), participants respond to the stimulus attribute that is either corresponding or noncorresopnding to the response attribute; for the Simon task (b), participants respond to the stimulus attribute that is neither corresponding nor noncorresponding to the response attribute, such as color, while S-R correspondence exists in some task-irrelevant stimulus attribute.

Figure 3. The stimulus-response compatibility (SRC) effect as a function of response mode (yoke-turn vs. button-press) and mapping condition (pure mapping vs. mixed mapping) in Yamaguchi & Proctor (2006, Experiments 3 and 4)

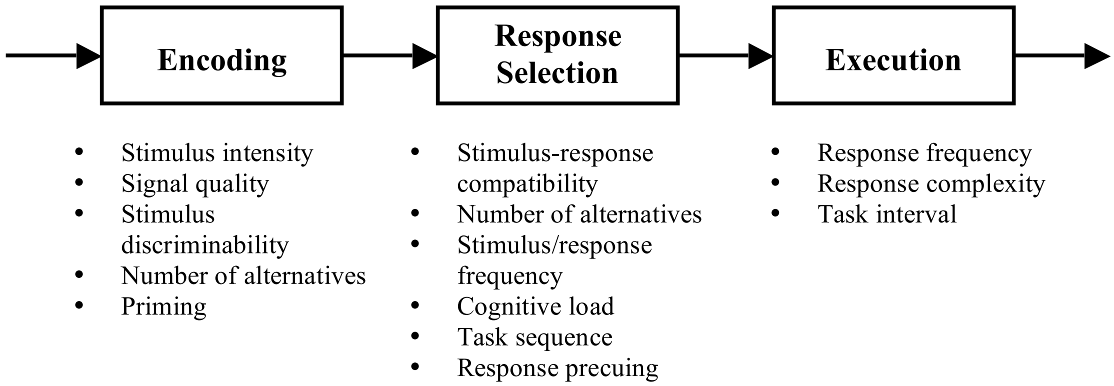
Figure 4. Mean response times for the compatible and incompatible mappings as a function of hand-mapping assignment in Proctor and Vu (2008, Experiment 3): L-C = Left hand/Compatible mapping, R-I = Right hand/Incompatible mapping, L-I = Left hand/Incompatible mapping, R-C = Right hand/Compatible mapping

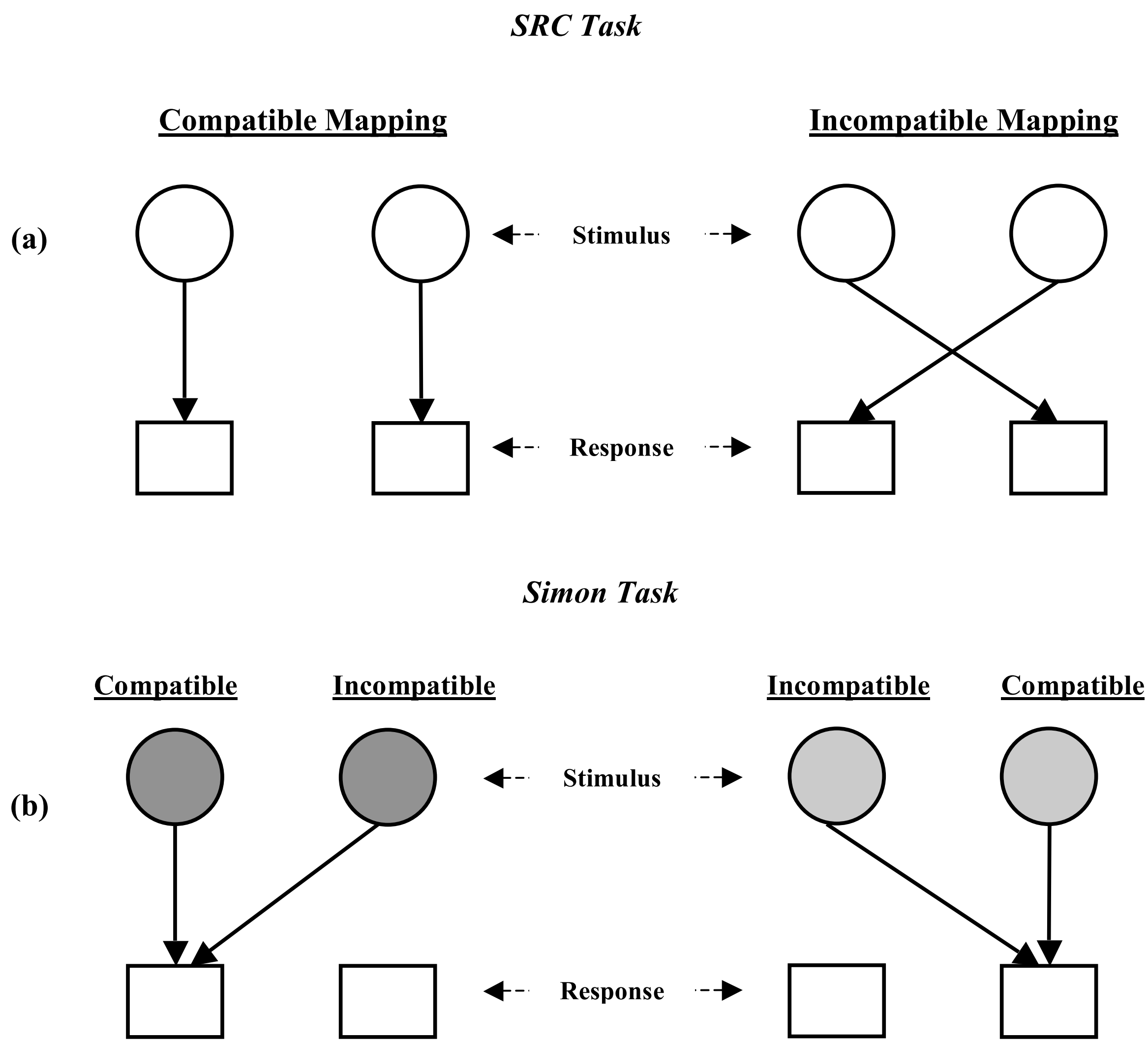
Figure 5. The Simon effect as a function of practice amount in Proctor, Yamaguchi, and Vu (2007, Experiment 1)

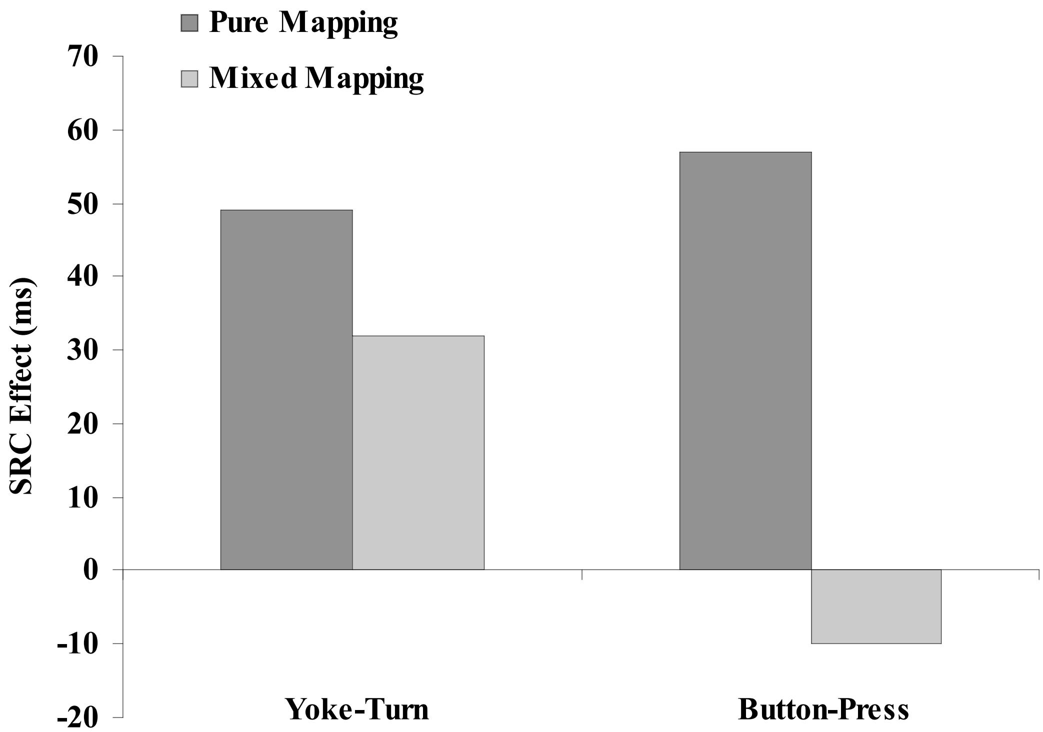
Figure 6. The Simon effect for the horizontal and vertical tasks as a function of practiced spatial dimensions in Proctor, Yamaguchi, and Vu (2007, Experiments 3 and 4)

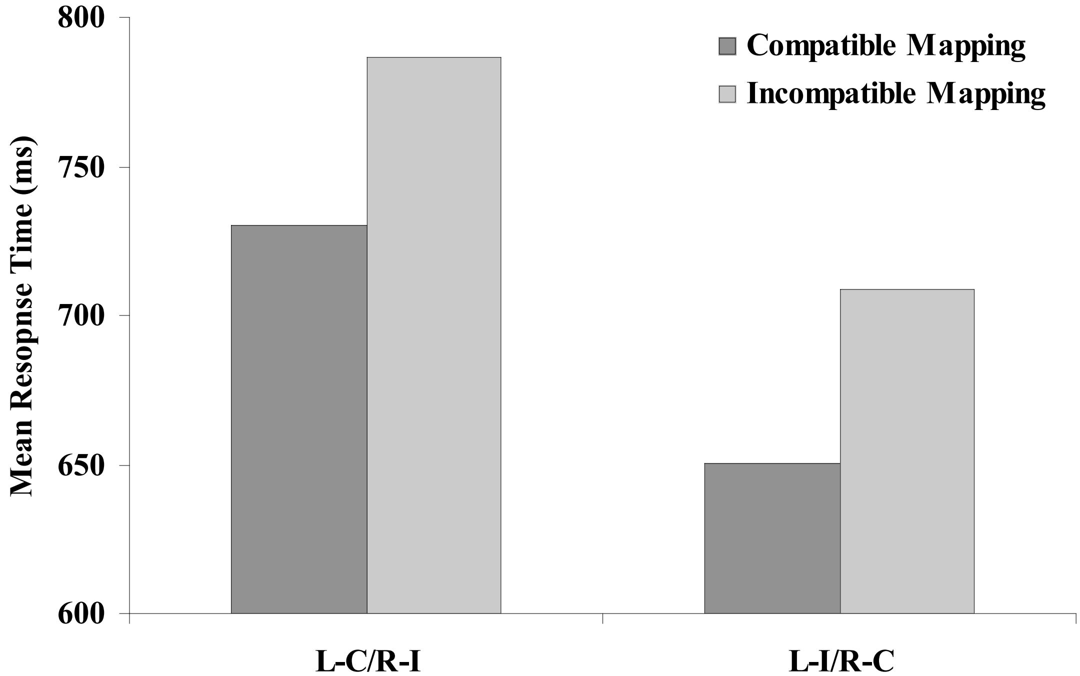
Figure 7. The Simon effect for the joystick and keyboard Simon tasks without action effect as a function of practiced response mode in Yamaguchi and Proctor (2008b, Experiment 2)

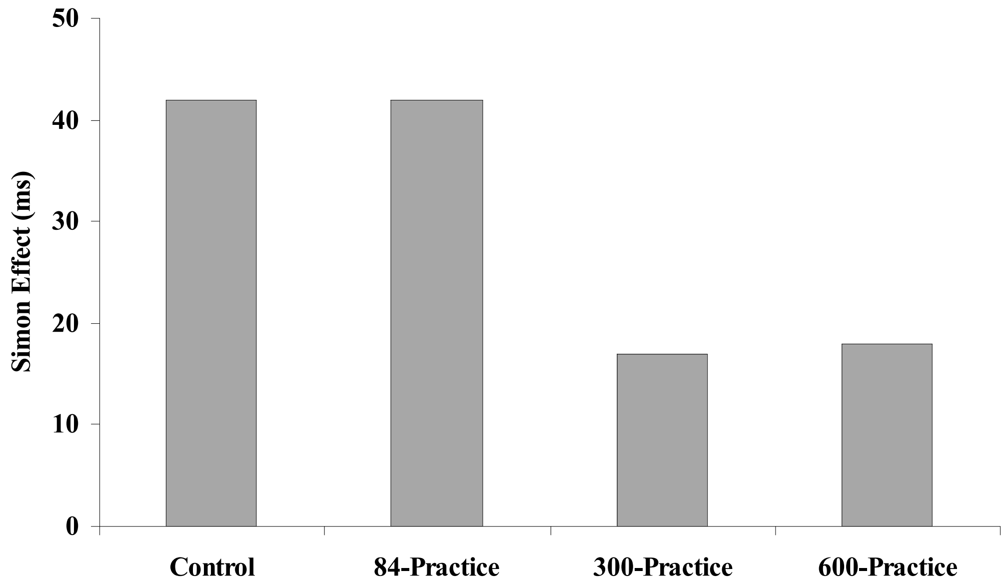
Figure 8. The Simon effect for the joystick and keyboard Simon tasks with action effect as a function of practiced response mode in Yamaguchi and Proctor (2008b, Experiment 3)


Encoding
Response Selection
Execution
• Stimulus intensity
• Signal quality
• Stimulus discriminability
• Number of alternatives
• Priming
• Stimulus-response compatibility
• Number of alternatives
• Stimulus/response frequency
• Cognitive load
• Task sequence
• Response precuing
• Response frequency
• Response complexity
• Task interval

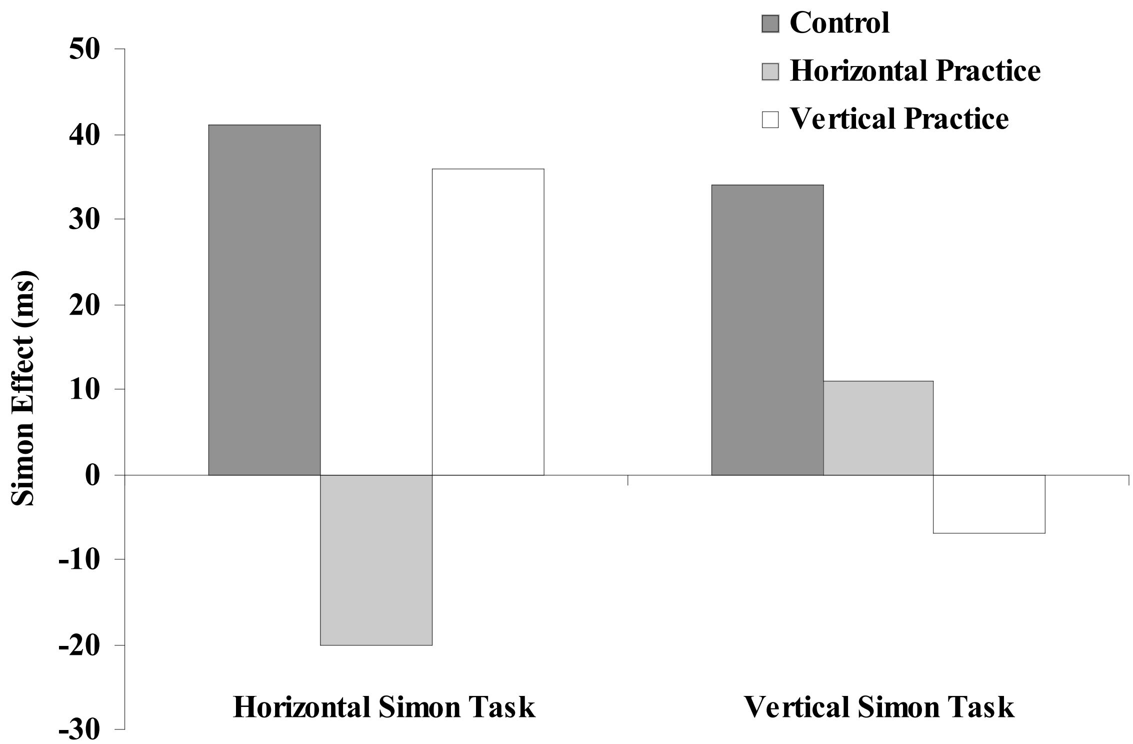

SRC Task
Compatible Mapping
Incompatible Mapping
(a)
Stimulus
Response
Simon Task
Compatible
Incompatible
Incompatible
Compatible
(b)
Stimulus
Response

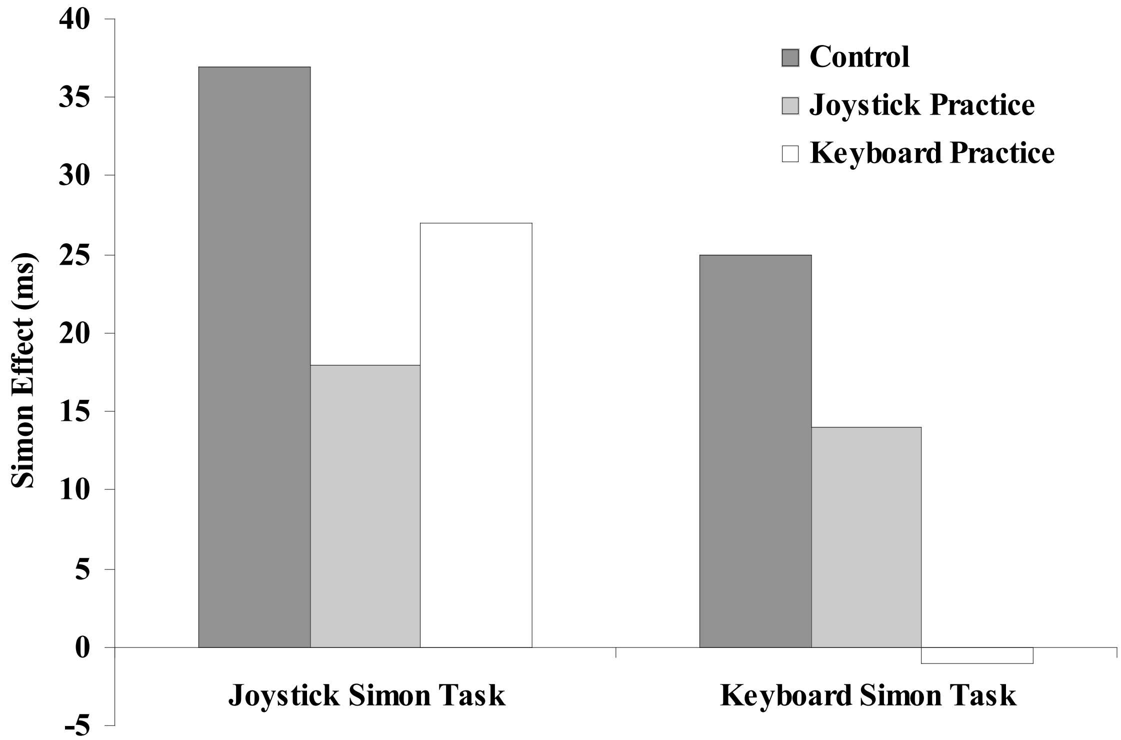

Pure Mapping
Mixed Mapping
SRC Effect (ms)
70
60
50
40
30
20
10
0
-10
-20
Yoke-Turn
Button-Press

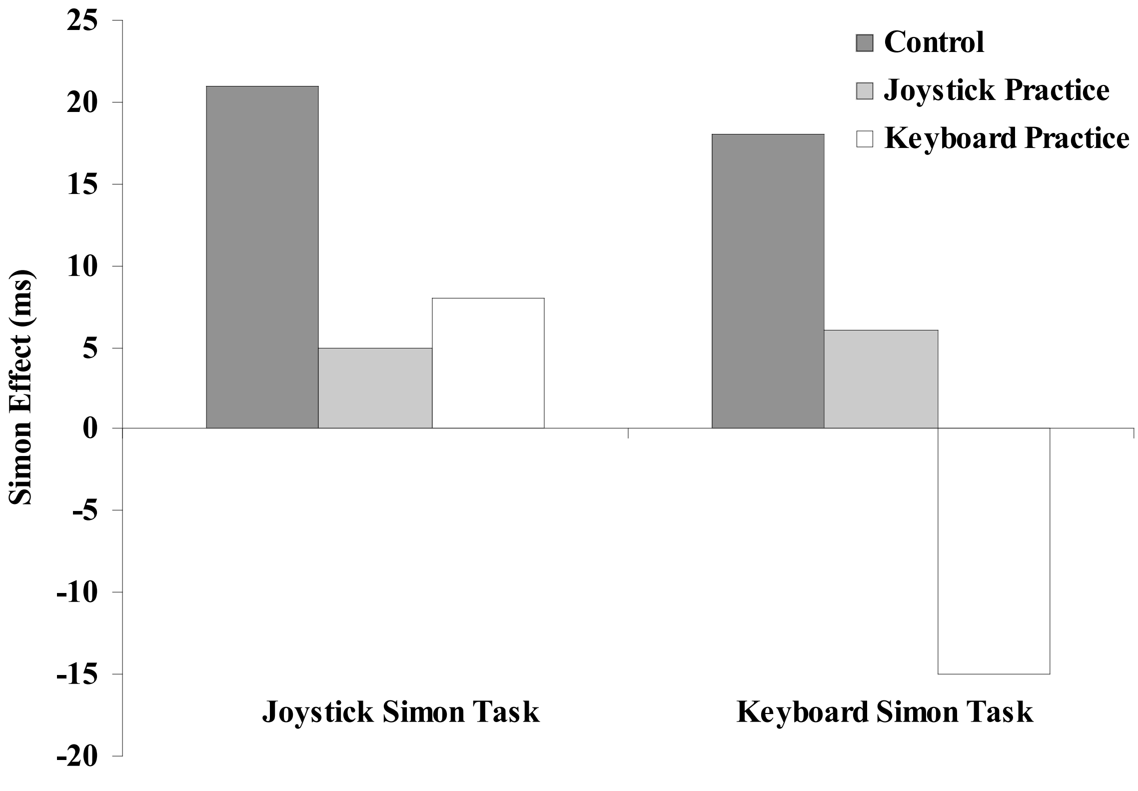

800
750
700
650
600
Mean Resopnse Time (ms)
Compatible Mapping
Incompatible Mapping
L-C/R-I
L-I/R-C



Simon Effect (ms)
50
40
30
20
10
0
Control
84-Practice
300-Practice
600-Practice


Control
Horizontal Practice
Vertical Practice
50
40
30
20
10
0
-10
-20
-30
Simon Effect (ms)
Horizontal Simon Task
Vertical Simon Task


40
35
30
25
20
15
10
5
0
-5
Simon Effect (ms)
Control
Joystick Practice
Keyboard Practice
Joystick Simon Task
Keyboard Simon Task



25
20
15
10
5
0
-5
-10
-15
-20
Simon Effect (ms)
Control
Joystick Practice
Keyboard Practice
Joystick Simon Task
Keyboard Simon Task