Implications of Compatibility and Cuing Effects for Multimodal Interfaces

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Abstract

Studies of stimulus-response compatibility show that certain stimulus modalities go more naturally with particular response modalities than others. For example, it is more natural to say the word “left” to a spoken word LEFT than to move a control left, whereas it is more natural to move a control left to a light onset to the left than it is to say the word “left”. Such modality relations determine not only how quickly a person can respond to relevant information but also the amount of interference that they may get from irrelevant distracting information. Cues that signal the spatial location of an upcoming target stimulus facilitate processing not only when the two stimuli are presented in the same modality but also when they occur in different modalities. In general, these crossmodal cuing effects occur when the cue and target stimulus are spatially co-located. In this paper, we review the findings on compatibility and cuing studies across stimulus modalities and discuss their implications for multimodal interface design.

1 Introduction

Multimodal interfaces are increasingly being used for a variety of purposes because they have the potential to facilitate effective and efficient interactions between humans and computers (Hempel & Altınsoy, 2005; Sorkin, 1987). The use of multiple display and control modalities enables different ways of presenting and responding to information, the incorporation of redundancy into displays, and emulation of real-life environments. Multimodal interfaces can reduce mental workload and make human-computer interactions more naturalistic. However, designing effective multimodal interfaces is a challenge because many interactive effects between different modalities may arise. These effects must be taken into account if the full benefits of multimodal interfaces are to be realized.

The present paper reviews findings from two areas of research that have direct implications for multimodal interface design. The first area, that of compatibility effects, examines performance as a function of the modalities of displays and controls and the individual mappings of display elements to control elements. The second area, that of cuing effects, examines interactions of spatial location information across different sensory modalities.

2 Compatibility Effects

In many applied contexts, people are required to make rapid and accurate controlling actions in response to different displayed events. Performance on these tasks can vary in efficiency as a function of the extent to which the required action to the event is consistent with the operator’s natural response tendencies, or, how compatible the stimuli are with the responses. Compatibility is particularly important to take into account for multimodal interfaces because compatibility effects occur for a variety of stimulus and response modes, are stronger for some modes than for others, and may have interactive effects across modes and tasks.

People's natural response tendencies for different display-control configurations have been documented in the literatures on *population stereotypes* for control-display mappings (Hoffmann, 1997) and *stimulus-response compatibility effects* (Hommel & Prinz, 1997). Several compatibility principles that have emerged from this research are summarized in Table 1.

Table 1: Compatibility Principles

- **Spatial Compatibility**
    - Compatible mappings of stimuli assigned to their spatially corresponding responses typically yield better performance.
    - Better performance occurs when the mapping of stimuli to responses can be characterized by a rule or relation than when it is random.
- **Movement Compatibility**
    - The motion of the display should move in the same direction as the motion of the control.
    - Clockwise movement is used to indicate upward movement or an increase in magnitude of the display.
- **Proximity Compatibility**
    - Controls should be placed closest to the display they are controlling.
    - Controls and displays should be arranged in functionally corresponding groups.
    - Control and displays should be sequentially arranged.
- **Mode Compatibility**
    - Better performance occurs when there is a match between display and control modes (visuospatial-manual and verbal-vocal) than when there is not.
    - Less interference from irrelevant information when it is conveyed by a different stimulus mode than the relevant information.
- **Others**
    - The up-right/down-left mapping is often better than the up-left/down-right mapping.
    - Pure tasks of a single stimulus-response mapping produce better performance than mixed tasks with multiple mappings.

Much of the research on stimulus-response compatibility effects has examined differences in performance for different mappings of stimuli to responses. In the simplest type of choice reaction task, involving two alternatives, a left or right keypress is made to a visual stimulus appearing on the left or right. The spatially corresponding mapping of left stimuli to left responses and right stimuli to right responses yields better performance (i.e., faster reactions and fewer errors) than the spatially non-corresponding mapping of left stimuli to right responses and right stimuli to left responses (e.g., Vu & Proctor, 2004). Mapping effects such as these, in which performance varies as a function of the mappings of individual stimulus and response elements within the same stimulus and response sets, are sometimes called element-level compatibility effects (Kornblum, Hasbroucq, & Osman, 1990). An interesting variant of spatial compatibility is the Simon effect, in which, when stimulus location is irrelevant and another dimension such as color is relevant, performance is still better when stimulus and response locations correspond than when they do not (see Simon, 1990, for a comprehensive review). Both stimulus-response compatibility proper and the Simon effect also occur for auditory (e.g., Roswarski & Proctor, 2000; Simon, 1990) and vibrotactile stimuli (Hasbroucq, Guiard, & Kornblum, 1989), as well as when the responses consist of left versus right footpedal responses (e.g., Vu & Proctor, 2001), movements of a joystick or switch to the left or right (e.g., Vu & Proctor, 2001), aimed movements of a finger to a left or right location (Wang & Proctor, 1996), or turns of a steering wheel clockwise (right) or counterclockwise (left; Proctor, Wang, & Pick, 2004).

Element-level compatibility effects occur not only when the stimuli differ in physical location but also when the spatial information is conveyed symbolically (e.g., left or right pointing arrow) or verbally (e.g., the word left or right; Vu & Proctor, 2004). Moreover, the responses can also be spoken directional words, such as "left" or "right" (Vu & Proctor, 2004). These outcomes indicate that compatibility effects occur both when there is physical similarity between the stimulus and response dimensions and when there is only conceptual similarity. Although a match between stimulus and response dimensions at the conceptual level produces a compatibility effect, the effect is typically smaller than when the dimensions also match at a physical, or mode, level as well. With visual stimuli, performance is better when the stimulus and response modes match (i.e., spoken responses are made to written location words or manual responses to visuospatial stimuli) than when they do not (i.e., spoken responses are made to visuospatial stimuli or manual responses to written location words; Wang & Proctor, 1996; see also Wickens, 1992). Such differences in mode relations are a type of set-level compatibility effect (Kornblum et al., 1990), that is, a difference in the compatibility of the overall stimulus set with the response set. According to Kornblum et al.'s dimensional overlap model, which attributes the set-level compatibility effects to stronger automatic activation of the corresponding response when set-level compatibility is high than when it is low, the high compatibility sets should yield both faster responses with a compatible mapping and slower responses with an incompatible mapping than the low compatibility sets. However, although the match between stimulus and response modes facilitates responding when the mapping is compatible (Kornblum & Lee, 1995; Proctor, Wang, & Vu, 2002), a mode mismatch does not necessarily cause interference when the mapping is incompatible (see Proctor et al., 2002). Greenwald (1970) proposed that ideomotor compatible stimuli and responses, that is, those for which the stimulus is similar to the sensory feedback provided by the response (e.g., saying the word "ten" in response to the spoken word "ten"), have a special advantage. According to Greenwald, response selection is bypassed when ideomotor compatible responses to stimuli are required because action is mediated by an image of the sensory feedback in this case.

Physical similarity is important in determining the amount of interference produced by irrelevant stimulus information. For example, Baldo, Shimamura, and Prinzmetal (1998) used left or right pointing arrows and the words left and right as stimuli. Robust Simon effects were obtained when the participants responded manually to the words, with the arrows being irrelevant, and when they responded vocally (saying "left" or "right") to the arrows while ignoring the irrelevant words. The effects of irrelevant information on performance were reduced substantially when the response mode was physically similar to that of the relevant stimulus dimension, that is, when responding manually to arrows and vocally to words. Lu and Proctor (2001) obtained similar results using stimuli for which a location word (left or right) was embedded inside of an outline arrow pointing to the left or right. When arrow direction was relevant, keypress responses showed little influence of the irrelevant location word, but when location word was relevant, keypress responses showed a substantial correspondence effect for irrelevant arrow direction.

Compatibility is a significant factor in dual-task performance. When the stimuli for two reaction tasks are presented close together in time, reaction time to the second task is typically slowed. This phenomenon is called the *psychological refractory period* (PRP) effect. Greenwald and Shulman (1973) provided evidence suggesting that no PRP effect occurs when both tasks are ideomotor compatible (e.g., moving a joystick left or right in response to a left or right arrow and saying "A" of "B" to the spoken letter A or B). Although the elimination of PRP effects has not been replicated in several recent experiments (Lien, Proctor, & Allen, 2002; though see also Greenwald, 2003; Lien, Proctor, & Ruthruff, 2003), the effect size is clearly much smaller than that obtained in most situations (see also Schumacher et al., 2001). Another finding of importance in the PRP literature is that crosstalk effects across tasks (similar to the Simon effect within a single task) occur in many situations, with a stimulus for one task tending to activate its corresponding response for the other task (e.g., Hommel, 1998). Interestingly, such crosstalk effects are largely absent when the two tasks are ideomotor compatible (Lien, McCann, Ruthruff, & Proctor, 2005). Discussion of a broader range of compatibility issues in dual-task performance can be found in Lien and Proctor (2002).

In addition to physical and conceptual similarity contributing to compatibility effects, it is generally accepted that what is called structural similarity contributes to performance as well (e.g., Cho & Proctor, 2003; Kornblum & Lee, 1995; Reeve & Proctor, 1984). That is, performance benefits when correspondence in the structure of the stimulus and response sets is maintained, even in the absence of physical or conceptual similarity. For example, performance is better when 10 digits are mapped to the 10 fingers of the hands in a left-to-right order than when they are randomly assigned. When a symbolic stimulus set composed from two values on each of two dimensions (e.g., letter identity and size) is mapped to a row of four response keys, performance is best when the most salient dimension corresponds with the salient distinction between the two leftmost and two rightmost responses (Proctor & Reeve, 1985). Additionally, when stimuli and responses vary along orthogonal spatial dimensions, the mapping of an upper stimulus location to a right response and lower stimulus location to a left response often produces better performance than the alternative mapping because it maintains correspondence between the positive and negative alternatives of the two dimensions (Cho & Proctor, 2003). The point is that in mapping stimuli from different modes to responses, one has to accommodate the properties of the entire stimulus and response sets, as well as those of the elements from which they are composed.

When the elements of the display and control configurations can be coded along two spatial dimensions simultaneously (i.e., when they are arrayed along a diagonal), compatibility effects occur for both dimensions. However, depending upon which dimension is made more salient by the stimulus-response configuration, the compatibility effect can be larger for one dimension than for the other. This prevalence of one dimension can occur regardless of whether the stimuli are presented visually or auditorily (Nicoletti & Umiltà, 1984, 1985), and no matter whether the responses are executed with both hands and feet, a single hand and foot (Rubichi, Nicoletti, Pelosi, & Umiltà, 2004), or with unimanual joystick movements (Vu & Proctor, 2001). Thus, the manner in which the display and control elements are configured can provide the basis for coding along the salient dimension when more than one spatial reference frame is provided. More generally, when stimulus and response sets can be coded with respect to more than one frame of reference, which pairings of stimuli and responses are most compatible is dependent upon the frames on which coding is based (Proctor et al., 2004).

Although compatibility effects are robust, occurring in essentially all stimulus and response modalities and even after extended practice, there have been several demonstrations that the benefit for spatial compatibility can be eliminated through the influence of other associations defined for a task performed prior to, or concurrent with, a spatially compatible task (e.g., see Proctor & Lu, 1999; Proctor, Vu, & Marble, 2003; Tagliabue, Zorzi, & Umiltà, 2002). Vu and Proctor (2004) showed that when set-level compatibility is high (i.e., the stimulus-response sets are visuospatial-manual or verbal-vocal), mixing compatible and incompatible mappings within a block of trials decreases overall task performance in comparison to when each mapping is performed in isolation, and, more important, eliminates the benefit for the compatible mapping. The cost of mixing on the compatibility effect can be reduced, though, by presenting the stimuli for each mapping in different stimulus modes (e.g., location words as stimuli for one mapping and physical locations as stimuli for the other; Proctor, Marble, & Vu, 2000; Proctor & Vu, 2002).

Although our discussion of compatibility effects has focused on stimuli and responses with spatial or directional properties, it is important to emphasize that compatibility effects for both relevant and irrelevant stimulus dimensions occur whenever there is any similarity, or overlap, between stimulus and response dimensions. For example, a Simon effect has been shown to occur on the basis of the irrelevant positive or negative affective content of words to which a vocal response "positive" or "negative" is to be made based on another stimulus attribute such as whether the word is a noun or verb (e.g., De Houwer, Crombez, Baeyens, & Hermans, 2001). A Simon effect has also been demonstrated to occur when responses of long and short durations must be made to stimuli that vary on an irrelevant dimension of duration (i.e., long vs. short; Kunde & Stöcker, 2002).

3 Cuing Effects

Like many studies on stimulus-response compatibility, studies on cuing effects typically also use reaction time and error rate as performance metrics (though see Prinzmetal, McCool, & Park, 2005). In a typical experiment using the *orthogonal cuing paradigm* (see Spence, McDonald, & Driver, 2004, and Driver & Spence, 2004, for recent reviews), a participant receives vibrotactile stimulation to the left or right hand (the cue) followed by the illumination of one of two visual LEDs held by the left or right hand (the target), and is asked to make a speeded response to indicate whether an upper or lower LED was illuminated by pressing one of two footpedals. Cuing effects are measured in terms of the difference in reaction times between the valid (when the cue and target occur on the same side) and invalid cuing conditions (when the cue and target occur on different sides). This difference in performance between valid and invalid trials has been taken as providing a measure of the extent to which the presentation of stimuli in one sensory modality can direct, or capture, *spatial* attention in another modality (e.g., Spence, 2001).

Auditory, visual, as well as vibrotactile stimuli have been examined in spatial cuing experiments. It has been demonstrated that the speeded detection of a visual target is faster and tends to be more accurate following the presentation of a spatially-noninformative peripheral auditory cue presented on the same side of the visual target rather than on the opposite side (e.g., Bolognini et al., 2005; Spence & Driver, 1997; see also Prinzmetal, Park, &

Garrett, in press). By contrast, speeded discrimination responses for auditory targets are only affected by the prior presentation of spatially noninformative visual cues under certain situations, but not others (see Ward, McDonald, & Lin, 2000; McDonald, Teder-Sälejärvi, Heraldez, & Hillyard, 2001; and see Spence et al., 2004, for a recent review). As far as the crossmodal pairing of visual and tactile stimuli goes, there is evidence that visual target judgments can be significantly affected by spatially non-predictive tactile cues, and vice versa (Spence, Nicholls, Gillespie, & Driver, 1998; Kennett, Eimer, Spence, & Driver, 2001; Kennett, Spence, & Driver, 2002; Gray & Tan, 2002; Tan, Gray, Young, & Traylor, 2003). Finally, spatially non-predictive tactile cues can also lead to significant crossmodal spatial-cuing effects upon auditory target judgments, and vice versa (Spence et al., 1998).

Most of the crossmodal (among vision, audition and touch) spatial-cuing effects discussed thus far fall into the category of *exogenous* (or involuntary) cuing, where attention to a spatial location is automatically elicited by the presentation of spatially non-informative peripheral cues at the same time as, or shortly before the onset of, the target stimuli. The orthogonal cuing paradigm is effective at eliciting exogenous cuing when the cues (typically presented on the left or right) do not predict the likely target location (e.g., up and down). The other type, *endogenous* orienting, is elicited if the participants are informed that the targets are more likely to occur at the cued location than at the non-cued location, or when an informative central arrow is used to indicate the likely site of target stimuli (see Driver & Spence, 2004, for a detailed review; see also Chambers, Stokes, & Mattingley, 2004). This is a voluntary form of directing one's spatial attention to the expected location. In addition to the simple target detection and discrimination tasks described above, many studies of crossmodal links in spatial attention have examined unspeeded temporal order judgments (e.g., Spence, Shore & Klein, 2001; Zampini, Shore, & Spence, in press), as well as perceptual sensitivity (e.g., Bolognini et al., 2005; Ho & Spence, in press; McDonald, Teder-Sälejärvi, & Hillyard, 2000; Prinzmetal et al., in press). Neuroimaging techniques, such as event-related potentials (ERPs) and functional magnetic resonance imaging (fMRI) have also been used to investigate the neural underpinnings of spatial attentional orienting (e.g., see chapters in Spence & Driver, 2004). We have chosen to focus our discussion on early (i.e., short SOA) exogenous crossmodal spatial-attention cuing using detection and discrimination latency tasks because of our interest in exploiting these results for the design of effective multimodal warning systems that can automatically capture a user's attention.

The issue of collocation is an important one in studies of crossmodal spatial attention. In general, performance is enhanced if information coming from more than one sensory modality is presented from approximately the same external location; and conversely, it is easier to reject distracting information presented at a different spatial location. Even when auditory and visual tasks are entirely unrelated, actively performing them together can be more efficient when the visual and auditory presentations originate from a common external spatial source, rather than from different locations. For example, Spence and Read (2003) reported that participants in a driving simulator found it easier to shadow (repeat) speech presented from the front of the vehicle (where visual attention is typically focused upon during driving; e.g., Lansdown, 2002) than that presented from the side. It has been suggested that some of the null crossmodal results found in earlier studies (e.g., Tassinari & Campara, 1996, using a tap on the shoulder and the illumination of a square on a screen) might have been due to the fact that the cue and target stimuli were presented from very different spatial locations even when they were on the same side with respect to the participant's torso (cf. Spence et al., 1998; although see later experiments by Tan et al., 2003, discussed below). The importance of collocation is further underscored by a recent study using moving cues. Gray and Tan (2002) suggested dynamic and predictive spatial links between touch and vision by demonstrating faster visual discrimination performance at the final tactile pulse location derived from moving tactile cues, and by demonstrating the dependence of tactile discrimination performance on the visual cuing object's time to contact.

An exception to the cue-target collocation rule is provided by a study of Tan et al. (2003) in which participants received vibrotactile cues on the four corners of their backs prior to searching for a visual change on a computer monitor. Participants were informed that the location of the tactile cue predicted the quadrant of the visual change on 50% of the trials, hence the task elicited both endogenous and exogenous spatial attention cuing. Tan et al. (2003) reported that visual detection time decreased significantly when the location of the tactile cue was in the same quadrant as that of the visual change, and that detection time increased significantly when the tactile cue and the visual target occurred in different quadrants. Another recent study by Ho, Tan, and Spence (2004; submitted) confirmed that crossmodal attention cuing effects can be elicited when the (tactile) cue and the (visual) target are presented from very different locations (so long as the direction in which the stimuli are presented was matched). In a simulated driving environment, participants felt a vibrotactile stimulus presented on the front or back around the waist, and were required to brake, accelerate or maintain constant speed by checking the front or the rearview mirror for a potential emergency driving situation (i.e., the rapid approach of a car from either in front or behind). It was found that participants responded significantly more rapidly following valid vibrotactile cues than following invalid cues. A further twist to the spatial setup of this experiment was that when prompted by a vibrotactile cue to the *back*, participants were able to look at the rearview mirror in the *front* in order to check the traffic condition *behind* the vehicle. Therefore, it would appear that the cue-target collocation rule can be relaxed when a tactile cue is involved, and when the spatial mapping between the cue and target is overlearned (such as in driving). This is a useful result that should be explored in designing multimodal warning systems. Whereas it is generally desirable to match the cue and target stimuli locations to maximize spatial cuing effects, tactile cues may be effectively deployed when it is not feasible to place warning signals at exactly the same location as that of dangerous events.

The relative effectiveness of vision and kinesthesis for crossmodal spatial attention cuing was examined by Klein (1977). He showed that whereas it takes the same amount of time to switch attention *from* vision and *from* kinesthesis, people can more rapidly switch their attention *to* kinesthesis than *to* vision. In general, kinesthetic stimuli seem to be superior to visual stimuli in alerting attention, and kinesthetic responses are generally faster (albeit less accurate) than visual or auditory responses (Robinson, 1934, Table 7). Klein (1977) speculated that our attentional bias to vision may stem from the relatively poor alerting capability of visual stimuli. Numerous studies have now shown that spatially non-informative tactile cues can effectively elicit an automatic exogenous shift of attention that facilitates subsequent responses to visual, audio and tactile stimuli (Spence et al., 1998; Spence & McGlone, 2001; Kennett et al., 2001; Kennett et al., 2002). Therefore, touch is an extremely effective modality for alerting. Touch stimuli with spatial information can potentially speed up visual response to pending hazardous situations. Given the effectiveness of exogenous cuing, there seems to be no need for extensive user training in order for a multimodal warning system to be highly effective.

4 Summary

Human factors specialists have recognized the importance of compatibility effects in designing interfaces since the earliest days of research in the field. However, the robustness of such effects and the fact that there are many aspects of compatibility that must be considered when designing multimodal displays have not been fully appreciated. Element-level compatibility effects, that is, differences in performance as a function of stimulus-response mapping, occur for a variety of situations in which the stimulus and response dimensions have some similarity. This similarity need not be spatial, nor does it need to be a physical, perceptual property. Compatibility effects can occur solely as a function of conceptual or structural similarity between stimulus and response sets, and thus will be evident across stimulus and response modalities as well as within them. It is important for designers to realize, though, that the set-level compatibility for certain combinations of stimulus and response modalities is higher than for others. Those combinations for which set-level compatibility is high, such as physical stimulus location and physical response location, will yield the best performance when the modality relation is relevant and the mapping of display and control elements is also compatible. However, when the modality relation is irrelevant, as when a relevant stimulus dimension such as color is responded to with a keypress and stimulus location is irrelevant, the most intrusion will tend to be observed. When compatible and incompatible mappings are mixed or multiple tasks must be performed, interactions among mappings and tasks often occur. In particular, the performance benefit of a compatible mapping is often drastically reduced. For multiple tasks, crosstalk between tasks can occur, and certain combinations of tasks are easier to perform together than others.

In recent years, numerous studies on cuing effects have suggested substantial spatial attentional links between vision, audition and touch. The consensus seems to be that auditory and tactile cues are more effective at directing visual attention than vice versa, although vision is still the preferred modality for detailed information processing. Auditory and tactile stimuli may be more automatically alerting than visual stimuli (e.g., see Posner et al., 1976; Klein, 1977). Spatially-informative as well as spatially-noninformative cues can effectively elicit shifts in spatial attention both in the same sensory modality and across modalities. Stronger cuing effects are achieved when the cue and target stimuli occur at the same spatial location, although non-collocated haptic cues can be just as effective when there is a logical mapping between the cue and target locations. In the context of designing multimodal warning signals, a recommended approach is to use spatial sounds or haptic cues to direct an operator's visual attention towards a critical location (e.g., the side of the vehicle with an impending collision, or an area on a large display that demands immediate action). Given that it is not always practical to deliver cues at the same location as that of an upcoming event, future research should focus on the conditions under which cues presented in the peripersonal space can be effectively used to elicit attention shift in the external space.

In the typical cuing task, the concern is primarily with directing attention to the location at which the target stimulus is expected to appear. Better performance for stimuli occurring at the cued location than at uncued locations is attributed to attention. Because the main purpose of cuing studies is to examine the facilitatory effects of spatial attention on stimulus identification, little consideration is typically given to which action is made in response to the stimulus. In contrast, in most compatibility studies, the concern is with the mapping or spatial correspondence between individual members of the stimulus set and individual members of the response set. Because of expected interactions between spatial cuing and compatibility effects, a more comprehensive approach to these effects would be to examine both together. As one example, the use of orthogonal cuing and stimulus (response) dimensions in cuing studies was intended to preclude response priming as a factor. However, stimulus-response compatibility effects can occur for orthogonal stimulus-response mappings (Cho & Proctor, 2003), even when stimulus location is irrelevant. Whether differential priming of responses occurs in the typical cuing task can be evaluated by examining correspondence effects between the cued location and the response location assigned to the target stimulus.

Interactions of other types between cuing and stimulus-response compatibility need to be examined as well. A tactual or auditory cue might be used to direct visual attention to a desired location, but it could have an inadvertent effect of priming the person to make a response corresponding to that location. Similarly, it may seem intuitive to use a warning signal to direct a person's attention toward the location of a potentially critical event, such as an impending collision with another vehicle. However, because this location is opposite to the direction in which the action should be taken to avoid the collision, any tendency that the warning induces to respond in the corresponding direction would be undesirable. Issues such as these are critical for the design of any multimodal interface that uses spatial information.

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