Stimulus–response compatibility in intensity–force relations

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Romaiguère, Hasbroucq, Possamai, and Seal (1993) reported a new compatibility effect from a task that required responses of two different target force levels to stimuli of two different intensities. Reaction times were shorter when high and low stimulus intensities were mapped to strong and weak force presses respectively than when this mapping was reversed. We conducted six experiments to refine the interpretation of this effect. Experiments 1 to 4 demonstrated that the compatibility effect is clearly larger for auditory than for visual stimuli. Experiments 5 and 6 generalized this finding to a task where stimulus intensity was irrelevant. This modality difference refines Romaiguère et al.’s (1993) symbolic coding interpretation by showing that modality-specific codes underlie the intensity–force compatibility effect. Possible accounts in terms of differences in the representational mode and action effects are discussed.

It is well established that performance in choice reaction tasks depends strongly on the compatibility of stimuli and responses (see Proctor & Reeve, 1990, for an overview). For example, a stimulus–response mapping (S–R) that requires a left-hand response to a stimulus on the left and a right-hand response to a stimulus on the right yields faster and more accurate responses than a mapping that reverses the S–R assignment. Likewise, if the stimulus set consists, for example, of the verbal stimuli red and green, pressing a key of the corresponding colour is more compatible than a reversed assignment. These tasks exemplify two broad classes of S–R compatibility effects, namely spatial and symbolic effects (Bashore, 1990).

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Romaiguère, Hasbroucq, Possamaï, and Seal (1993) reported a new compatibility effect that is not easily integrated into these traditional classes. In the compatible condition, their participants were to respond with a strong thumb press to a bright stimulus and with a weak thumb press to a dim stimulus. This S–R assignment was reversed in the incompatible condition. The results demonstrated a clear intensity–force compatibility effect on reaction time (RT), in that RTs were shorter in the compatible than in the incompatible condition.

This new compatibility effect is theoretically important because it shows that compatibility effects also occur when stimuli and responses vary along different physical dimensions (e.g., stimulus intensity and amount of force output) in contrast to traditional spatial compatibility tasks where stimuli and responses vary along the same physical dimension (e.g., side of stimulus and side of response). Romaiguère et al. (1993) favour a symbolic S–R transformation account to explain their finding. The codes involved in the symbolic transformation can be thought of as semantic codes that are independent of sensory and response modalities.

It has been assumed that symbolic effects occur when stimuli and responses share common linguistic labels (Bashore, 1990). In most compatibility tasks, these linguistic labels are identical for stimuli and responses (e.g., colour names). This does not necessarily apply, however, to intensity–force compatibility because the stimuli are dark and bright whereas the responses are weak and forceful. Thus it is unclear whether a symbolic S–R account applies to the phenomenon of intensity–force compatibility.

Nevertheless, there is evidence suggesting that stimuli and responses might well be coded in a common format at a more abstract linguistic level. For example, Walker and Smith (1984) demonstrated that the frequency of a tone exerts Stroop-like interference on adjectives that are only loosely associated with tone frequency. In one experiment the words bright and light were assigned to one response, and their antonyms dull and heavy were assigned to a different response. Each presentation of one of the words on a computer screen was accompanied by a tone of 50 or 5500 Hz. Although tone frequency was uncorrelated with the words, responses to bright and light were faster when a word was accompanied by a 5500-Hz tone than when it was accompanied by a 50-Hz tone. Likewise, RTs were shorter when a 50-Hz rather than a 5500-Hz tone accompanied the stimuli dull and heavy. Similar results were obtained for a variety of adjectives. Even the adjectives happy/cheerful versus gloomy/sad showed a Stroop-like interference (26 ms) with the irrelevant tones. According to Walker and Smith (1986, p. 492) this pattern of effects suggests that there is an abstract semantic dimension that embraces a large number of related concepts like strong, intense, bright, light, and loud, and that responses are faster when multiple stimuli are congruent with respect to this code.

Accordingly, one may assume that in the experiment of Romaiguère et al. (1993) the brightness of the light was recoded to such an abstract binary code, representing broad semantic categories of largeness versus smallness. This binary information is sufficient to select between two alternative response force levels. According to this hypothesis, bright and dim visual stimuli as well as strong and weak responses are recoded to higher linguistic categories, such as large and small. Then, with compatible intensity–force mapping, the match of stimulus and response codes is assumed to have a facilitating influence whereas the incompatible mapping has an inhibitory influence due to the mismatch of S and R codes. This linguistic coding hypothesis assumes that the effect is based on binary categories of an abstract semantic level (e.g., large vs. small).
Before, however, such an elaborated state of cognitive representation is achieved, the stimulus must necessarily undergo several transformations, because at an earlier level of sensory coding the representations are closely related to the physical properties of the stimuli. In contrast to linguistic codes, which contain highly aggregated information just sufficient to solve the task (e.g., large vs. small), these non-linguistic codes contain information that change in an analogue manner with the physical properties of the stimulus, such as stimulus intensity. Hence, we assume these analogue codes derived at an earlier level are involved in the S–R translation, and we refer to this view hypothesis in terms of the analogue coding hypothesis. The assumption of analogue codes is consistent with the finding that stimulus intensity, even when being completely task irrelevant, nevertheless increases response force when force is measured as a dependent variable in RT experiments (Angel, 1973; Jaśkowski, Rybarczyk, Jaroszyk, & Lemański, 1995; Miller, Franz, & Ulrich, 1999; Ulrich, Rinkenauer, & Miller, 1998).

The hypotheses of analogue coding and linguistic coding are reminiscent of earlier suggestions in terms of salient feature coding put forward by Proctor and colleagues (cf., Cho & Proctor, 2001; Proctor, Reeve, & Van Zandt, 1992; Weeks & Proctor, 1990) and by Umilta’s (1991; see also Adam, Boon, Paas, & Umilta, 1998) re-interpretation of the salient feature hypothesis. According to the salient feature principle, response selection is more efficient when salient features of the stimulus and the response correspond than when they do not. For example, when stimuli are arranged vertically, and responses are arranged horizontally, there is an advantage for the up-right/down-left over the up-left/down-right mapping; this is the so-called orthogonal compatibility effect. Weeks and Proctor (1990) suggested that up and right are the polar referents of the vertical and horizontal dimension; hence, S–R translation is more efficient when the polar referent of the stimulus dimension is mapped to the polar referent of the response dimension. In contrast to this view, Umilta (1991) limited the proposed asymmetry to verbal codes, claiming that spatial codes are symmetric and do not have polar referents. That is, verbal codes have the salient features of up and right actually producing the orthogonal S–R compatibility effect. Likewise, one might argue that stimulus intensity is coded verbally, as suggested by the linguistic coding hypothesis, and that verbal asymmetries produce the intensity–force compatibility effect.

To distinguish between the two S–R translation hypotheses in terms of linguistic and analogue coding, we examined whether intensity–force compatibility depends on sensory modality (visual vs. auditory stimuli) and on intensity levels of the stimuli employed in each modality. If stimulus coding is of a linguistic type based on aggregated stimulus information, we expected that such manipulations should have little impact on S–R transformation and thus on the size of the intensity–force compatibility effect. In contrast, modality–specific coding of bright and dim stimuli in vision and of loud and soft stimuli in audition appears to be associated with differences in the saliency of the respective codes. Accordingly, stimulus modality should change the force–compatibility effect.

Stimulus intensity may be physically manipulated in two ways. First, the difference between the bright and dim intensity levels can be manipulated, and second, the average intensity level can be manipulated. According to the linguistic coding hypothesis, neither stimulus modality nor stimulus intensity should modulate the size of the intensity–to–force compatibility effect. This is because stimulus intensity is transformed in a binary fashion to the amodal semantic concepts of small or large. By contrast, if stimulus intensity or sensory modality modulates the size of the effect, this would suggest that the codes still contain
information about the physical properties of the stimuli, as the analogue coding hypothesis would suggest.

The following experiments were conducted to assess the effects of modality and stimulus intensity on intensity–force compatibility. Experiment 1 was a replication of the study of Romaiguère et al. (1993) to enhance the comparison of compatibility effects across the experiments in this article. Experiment 2 employed auditory stimulation to test whether the effect is modality independent, as the linguistic coding hypothesis would suggest. Experiments 3 and 4 were mainly replications of Experiments 1 and 2 with different stimulus intensities. Experiments 5 and 6 employed the so-called Simon task (cf., Simon, 1990). This task was used to assess whether the codes that are responsible for the intensity–force compatibility effects are formed automatically.

**EXPERIMENT 1**

Experiment 1 was meant to replicate the compatibility effect reported by Romaiguère et al. (1993). Participants pressed a force-sensitive key with the index finger of their preferred hand. In one half of the experiment they had to respond as fast as possible with a weak keypress to a dim stimulus and with a strong keypress to a bright stimulus (compatible condition). In the other half, the assignment of the two stimuli to the two responses was reversed (incompatible condition)—namely, a weak keypress when stimulus intensity was high and a strong keypress when intensity was low. According to Romaiguère et al. the compatible condition should yield especially fast RTs.

**Method**

**Participants**

A total of 10 female and 10 male students (mean age 25.9 years) participated in a single session that lasted about 50 minutes. All participants had normal or corrected-to-normal vision, and all but one claimed to be right-handed. They received either course credit or 10 DM (about 5€).

**Stimuli and apparatus**

The participants were seated at a table in a dimly illuminated room. A chin rest stabilized the participant’s head at a distance of 70 cm from the computer screen. A microcomputer controlled stimulus presentation and the recording of response force. Filled circles and diamonds (about 2.2°) with two easily distinguishable intensities (0.53 or 19 cd/m²) served as stimuli on a dark background (0.08 cd/m²). The shape of the stimulus was only task relevant in Experiment 5, and thus the rationale of this manipulation becomes clear in Experiment 5. The four stimuli (circle and diamond, each dim or bright) were presented in random order with equal frequency. A small cross (about 0.8°) in the centre of the screen served as a warning signal.

Response force was measured by means of a force–sensitive key that consisted of a leaf spring (110 × 19 mm) with strain gauges attached to it. The leaf spring was fixed at one end, and any force applied to the free end was sampled at a rate of 500 Hz throughout the whole trial. The participant pressed this key with the index finger of his or her preferred hand while the forearm rested comfortably on the table. RT was measured as the interval between the onset of the response signal and the point in time when response force attained a criterion force of 50 cN. Peak force was determined in each trial.
**Procedure**

In each trial, participants were required to respond to the stimulus as fast as possible with a weak (< 600 cN, but above the criterion force of 50 cN) or strong (>600 cN) keypress according to stimulus intensity. To familiarize the participants with the force key and the required force levels of the response, they were asked to perform a few practice responses with feedback on the produced peak forces at the beginning of the session. The participants had no difficulty producing peak forces in the required force ranges.

In the compatible condition an instruction on the screen informed the participants that a dim stimulus would require a weak keypress whereas a bright stimulus would require a strong keypress. In the incompatible condition this assignment was reversed. The participants were further told that the shape of the stimulus (circle or diamond) should be ignored. The change from the compatible to the incompatible mapping, or vice versa, was announced after the 6th of 12 blocks. Half of the participants began with the compatible condition.

A trial started with the presentation of the visual warning signal for 300 ms. After a constant foreperiod of 1500 ms, the stimulus was presented for 300 ms, and the participants responded as fast as possible with the appropriate response force. Any error was immediately displayed after the response (e.g., too slow, too weak, or too strong). The next warning signal was presented 1 s later. At the end of a block of 50 trials visual feedback on mean RT and on the number of errors was displayed to keep motivation high.

**Design**

Stimulus intensity (low vs. high) and target force level (weak vs. strong) were the two factors of interest. Dependent variables were RT and various response errors. Mean RTs of correct trials and mean response errors were computed for each participant and each condition. A separate analysis of variance (ANOVA) was conducted for each dependent variable. An intensity–force compatibility effect on RT implies a significant interaction of the factors stimulus intensity and target force.

**Results**

The average peak force was 275 cN for the weak response condition (peak force between 50 and 600 cN) and 1727 cN for the strong condition (>600 cN).

**Response errors.** An ANOVA was performed on arcsine transformed error rates (Winer, 1971). Participants failed to produce the appropriate response force in 3.3% of the trials when a weak response was required and in 2.2% of the trials with strong responses. This difference suggests that it was slightly more difficult to produce a weak keypress than a strong keypress, though the effect just failed to reach significance, \(F(1, 19) = 4.3, p = .052\). The frequencies of anticipatory responses (RT < 100 ms) and of responses that were too slow (RT > 1000 ms) were each below 1% and hence too low to permit a meaningful statistical analysis. Error trials were discarded from further analysis.

**Reaction time.** The upper left panel of Figure 1 shows the mean RT as a function of stimulus intensity and target force. Strong responses were carried out faster than the weak responses (423 vs. 451 ms), \(F(1, 19) = 40.4, p < .001\), and the responses to stimuli of high intensity were faster than those of low intensity (425 vs. 450 ms), \(F(1, 19) = 27.0, p < .001\). More important,
however, these two factors produced a significant interaction, $F(1, 19) = 6.1, p < .05$.\(^1\) Compatible responses were carried out faster than incompatible responses (420 vs. 455 ms). This interaction replicates the compatibility effect reported by Romaiguère et al. (1993).\(^2\)

**Discussion**

This experiment successfully replicated the results of Romaiguère et al. (1993). RTs were shorter for stimuli of high intensity than for those of low intensity and also shorter for strong

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\(^1\) Note that this interaction is equivalent to a statistical comparison of the means in the two compatible conditions (weak responses to stimuli with low stimulus intensity and strong responses to stimuli with high stimulus intensity) with the means of the two incompatible conditions (weak/high and strong/low). The size of the compatibility effect is then given by the average of the means in the incompatible conditions minus the average of the means in the compatible conditions.

\(^2\) The present interaction is noticeably less symmetrical than that reported by Romaiguère et al. (1993). This is, however, only due to the fact that the main effects in the present experiment were relatively large as compared to the size of the interaction. For example, the low-intensity/weak-force condition appears to have little advantage over the low-intensity/strong-force condition. However, strong responses are generally carried out faster than weak responses, which might be due, for example, to the larger target force window for the strong force condition. It is therefore not warranted to conclude that the compatibility effect is diminished in one or the other condition.
than for weak responses. Consistent with their study, there was a clear intensity–force compatibility effect on RT. Responses in the compatible intensity–to–force mapping condition were faster than responses in the incompatible condition. This RT advantage for compatible over incompatible mappings can be accounted for by the coding view of S–R compatibility, which assumes the formation of codes for stimulus and response features that may either match or mismatch (e.g., Hasbroucq, Guiard, & Ottomani, 1990; Hommel, 1993; Kornblum, Hasbroucq, & Osman, 1990; Proctor et al., 1992). Accordingly, participants form such codes for stimulus intensity and response force. Then, when stimulus intensity and response force codes mismatch, additional S–R processing is required to resolve the response conflict, and this increases RT.

EXPERIMENT 2

The procedure of Experiment 2 was identical to that of Experiment 1 except for the use of auditory instead of visual stimuli. In the compatible condition, participants were to produce a weak response to a soft tone and a strong response to a loud tone. As in Experiment 1, this assignment was reversed in the incompatible condition. The tones varied not only in intensity but also in frequency. (Frequency, however, was task irrelevant, just like the shape of the visual stimuli in Experiment 1, and the rationale becomes clear in Experiment 6.) As discussed in the Introduction, symbolic coding of stimulus intensity suggests that the size of the compatibility effect should not vary with sensory modality, at least if symbolic codes contain binary information about the level of stimulus intensity. More precisely, Experiment 2 should provide a compatibility effect that is not significantly different from the 35-ms effect of Experiment 1.

Method

Participants, stimuli, and procedure

A fresh sample of 12 female and 8 male students (mean age 24.8 years, all right handed) participated in this experiment. The procedure was almost identical to that of Experiment 1, with visual stimuli replaced by auditory ones. The warning signal was a short click of 10–ms duration and at a sound pressure level (SPL) of 60 dB(A). The response signal was a tone of 300–ms duration with intensity levels of 50 or 70 dB(A). Half of the tones of each intensity level had a frequency of 800 Hz, and the other half had a frequency of 1200 Hz.

Results

The average peak forces were almost identical to those observed in Experiment 1. The mean peak force was 262 cN for the weak response condition and 1689 cN for the strong condition.

Response errors. There were 0.5% premature responses (<100 ms) and 1.9% slow responses (>1000 ms). As in Experiment 1 and as to be expected, there were fewer force errors (too weak or too strong) in compatible blocks (2.8%) than in incompatible blocks (3.8%), $F(1, 19) = 7.1$, $p < .05$. 
Reaction time. As can be seen in the lower right panel of Figure 1, the RT results clearly confirmed the compatibility effect of Experiment 1. Compatible responses were much faster than incompatible responses (429 vs. 549 ms), \( F(1, 19) = 123.7, p < .001 \). There was also a main effect of target force level, \( F(1, 19) = 19.9, p < .001 \), with faster responses when a strong response was required than when a weak response was required (472 vs. 506 ms). There was, however, no effect of stimulus intensity on RT, \( F < 1 \).

Discussion

As in Experiment 1, RTs were shorter for strong than for weak responses. More important, responses in the compatible intensity-to-force mapping condition were again faster than responses in the incompatible condition. This result indicates that the original intensity-force effect observed by Romagnuère et al. (1993) can be generalized to auditory stimulation. The RT advantage for compatible over incompatible intensity-to-force mappings can be accounted for by assuming that response conflicts in incompatible conditions delay the execution of the response.

Theoretically more important, however, is the fact that the compatibility effect with auditory stimulation was much larger than that with visual stimulation in Experiment 1 (120 vs. 35 ms), \( t(38) = 4.80, p < .001 \). This finding does not support the linguistic coding hypothesis. As argued in the introduction, if such linguistic codes were the source of interference, then the intensity-force compatibility effect should not depend on sensory modality. The large difference, however, suggests that the codes incorporate information about physical stimulus features like modality and intensity, which in turn influence response selection.

This conjecture needs further experimental support, however, because the difference in stimulus intensity turned out to be larger for auditory than for visual stimuli when transformed onto a common intensity scale. According to the transformation rule suggested by Stevens (1955), the resulting intensity difference for visual stimuli of 15.5 dB is indeed somewhat smaller than the 20.0-dB difference for the auditory stimuli employed in Experiment 2 (50 vs. 70 dB). Thus, the observation of a larger compatibility effect for auditory stimuli might be attributed to a larger difference in stimulus intensities.

The following two experiments assessed whether the large difference in compatibility effects with auditory stimuli as compared to visual stimuli was due to a difference in stimulus modality or merely due to a larger effective intensity difference in Experiment 2 than in Experiment 1. In other words, the larger compatibility effect in Experiment 2 than in Experiment 1 could have resulted from a larger difference in stimulus intensity between the two auditory stimuli (20.0 dB) than between the two visual stimuli (15.5 dB). Thus, Experiment 3 employed visual stimuli with a considerably enlarged intensity difference (29.1 dB), and Experiment 4 employed auditory stimuli with a decreased intensity difference (10.0 dB) to test this possibility. That is, if the size of the intensity-force compatibility effect depends mainly on intensity differences, then one should expect a larger compatibility effect for visual than for auditory stimuli.
EXPERIMENT 3

This experiment was identical to Experiment 1 (visual modality) except for a larger difference in stimulus intensity.

Method

Stimulus luminances were now 0.17 cd/m² (57.3 dB) and 139.5 cd/m² (86.4 dB) on a dark background (0.08 cd/m²). The resulting intensity difference of 29.1 dB was clearly above the difference of 20.0 dB that was employed in Experiment 2 with auditory stimuli. A fresh sample of 10 female and 10 male students (mean age 28.7 years, all but two right-handed) participated in this experiment.

Results

Average peak force was 245 cN for the weak response condition and 1426 cN for the strong condition.

Response errors. There were 0.5% premature responses (<100 ms) and 1.9% slow responses (>1000 ms). There were again fewer force errors (too weak or too strong) in compatible blocks (2.1%) than in incompatible blocks (2.9%), \( F(1, 19) = 5.8, p < .05 \).

Reaction time. The panel on the lower left side of Figure 1 shows that the pattern of results closely resembled the results of Experiment 1. There was again a clear effect of intensity–force compatibility on RT (424 vs. 483 ms), \( F(1, 19) = 15.9, p < .01 \). There were also main effects of stimulus intensity, \( F(1, 19) = 74.8, p < .001 \), with faster responses to the bright stimulus (476 vs. 431 ms), and of target force level, \( F(1, 19) = 12.5, p < .01 \), with faster responses when a strong response was required (439 vs. 468 ms).

Discussion

The results of Experiment 3 do not support the notion that the size of the compatibility effect increases as the difference of the intensity levels is increased. The results, however, strengthen the interpretation of the large compatibility effect observed in Experiment 2 as being specific for the auditory modality. Although the intensity difference of the two visual stimuli was increased drastically, the effect (59 ms) was nevertheless significantly smaller than that with auditory stimuli in Experiment 2 (120 ms), \( t(38) = 3.19, p < .01 \). On the other hand, the 59-ms effect did not exceed significantly the 35-ms effect of Experiment 1, \( t(38) = 1.18, p > .2 \).

EXPERIMENT 4

Experiment 4, we employed auditory stimuli with a relatively small intensity difference of 10.0 dB (40 vs. 50 dB) to put the hypothesis that intensity–force compatibility is generally larger for auditory stimuli to an even more rigorous test. If the modality hypothesis is true, the compatibility effect should still not fall significantly below the 59-ms effect that was obtained in Experiment 3 with visual intensities that differed by 29.1 dB. Note that the higher of the two intensities that are employed in Experiment 4 (40 vs. 50 dB) was the lower of the two intensities of Experiment 2 (50 vs. 70 dB).
In Experiment 2 the frequency of the tones was varied additionally (800 vs. 1200 Hz). Wood (1975) found that choice reactions to the intensity of sounds were slower when the pitch of the sounds, though irrelevant, was also varied. With the soft sounds and the small intensity difference (40 vs. 50 dB) discrimination could become too difficult when frequency was variable again. Therefore, in contrast to Experiment 2, the tones were now all of the same frequency (1000 Hz).

Method

A fresh sample of 17 female and 3 male students (mean age 25.6 years, all but one right-handed) participated in this experiment.

Results

Average peak forces were 286 cN for the weak response condition and 1407 cN for the strong condition.

Response errors. There were 0.8% premature responses (<100 ms) and 1.6% slow responses (>1000 ms). A significant interaction of target force level and stimulus intensity on force errors, $F(1, 19) = 18.1, p < .001$, showed that there were again fewer force errors (too weak or too strong) in compatible blocks (2.6%) than in incompatible blocks (3.7%).

Reaction time. The panel on the upper right side of Figure 1 shows that the main result could again be replicated. There was a clear effect of intensity–force compatibility on RT (439 vs. 534 ms), $F(1, 19) = 57.8, p < .001$. Strong responses were faster than weak responses (465 vs. 509 ms), $F(1, 19) = 51.5, p < .001$, whereas stimulus intensity showed no significant main effect, $F < 1$.

Discussion

The most important result from Experiment 4 is that the compatibility effect was again relatively large even though the difference in intensity was reduced strongly. The comparison of the effect sizes of Experiment 3 (59 ms) and Experiment 4 (95 ms) approached significance, $t(38) = 1.9, p = .069$. On the other hand, the present 95-ms effect was not significantly different from the 120-ms effect of Experiment 2, $t(38) = 1.5, p = .137$. The whole pattern of results (see Figure 1) clearly suggests that the intensity–force compatibility effect depends strongly on sensory modality, whereas the actual difference in physical stimulus intensity exerts little or at least no reliable influence. We discuss the implications of this pattern of results in the General Discussion.

The following two experiments addressed the question of whether the modality difference generalizes to a situation where stimulus intensity is task irrelevant. Irrelevant stimulus attributes have been shown to produce compatibility effects in other tasks—for example, in the Simon task (for a review, see Simon, 1990) or in the Stroop task (Stroop, 1935). To account for these effects, it is assumed that a stimulus code is formed automatically for the task–irrelevant stimulus dimension and that this code influences the selection of the appropriate response code. If the codes that are responsible for the modality difference of the intensity–force
compatibility effects are also formed automatically, one should expect a similar modality difference when intensity is irrelevant.

EXPERIMENT 5

In Experiments 1 to 4 stimulus intensity specified target force, and a correspondence effect was obtained. In Experiment 5 we tested whether a similar effect emerges when visual stimulus intensity is irrelevant for performing the task. In this experiment the shape of the stimulus (circle vs. diamond) specified the target force level of the response, with stimulus intensity being task irrelevant.

Method

Participants

A total of 12 female and 8 male students (mean age 24.8 years) took part in a single session in exchange for course credit or money. None had participated in any of the previous experiments. All participants had normal or corrected-to-normal vision, and all claimed to be right-handed.

Procedure

The method was identical to that of Experiment 1 except for the task-relevant stimulus dimension. Because the participants responded to the shape of the stimulus, corresponding and non–corresponding trials were now mixed within each block. Half of the participants were asked to respond to the circle with a strong keypress and to the diamond with a weak keypress, whereas the other half received the reverse instructions.

Results

Weak responses were carried out with 225 cN and strong responses with 1683 cN average peak force.

Response errors. Anticipatory and slow responses were again rare (<1%). As in Experiment 1, incorrect force production occurred more frequently when a weak response was required than when a strong response was required (3.2 vs. 1.9%), $F(1, 19) = 10.7, p < .01$. There were 1.9% force errors in corresponding conditions but 3.2% in non–corresponding conditions, $F(1, 19) = 25.6, p < .001$. As in Experiment 1, all incorrect trials were discarded from data analysis.

Reaction time. Mean RT as a function of stimulus intensity and force level is depicted in the left panel of Figure 2. Although the effect size was greatly reduced, there was nevertheless a significant correspondence effect. RTs in the strong force condition were again shorter than in the weak force condition (427 vs. 469 ms), $F(1, 19) = 13.4, p < .01$, and RTs to intense stimuli were shorter than those to less intense stimuli (437 vs. 459 ms), $F(1, 19) = 58.9, p < .001$. Crucially, however, significantly shorter mean RTs were again observed in corresponding than in non–corresponding trials (444 vs. 452 ms), $F(1, 19) = 6.4, p < .05$. 


**Discussion**

This experiment demonstrates that the effect of intensity–force compatibility is also obtained when stimulus intensity is task irrelevant. This finding suggests that stimulus intensity codes are automatically generated that influence the subsequent response selection.

The effect of intensity–force correspondence in this experiment was, though statistically significant, nevertheless relatively small. Whereas in Experiment 1 a 35-ms S–R compatibility effect was obtained when stimulus intensity was task relevant, this effect tended to decrease to an 8-ms effect when intensity was task irrelevant, \( t(38) = 1.82, p = .077 \). It should be noted, however, that a decrease in the spatial S–R compatibility effect is also obtained when stimulus location is task irrelevant. For example, Leuthold (1994) found a spatial S–R compatibility effect of 27 ms, which decreased to 17 ms when stimulus location was task irrelevant under otherwise identical visual stimulation conditions (see also Hasbroucq & Possamai, 1995).


**EXPERIMENT 6**

The procedure of Experiment 6 was identical to that of Experiment 5, except that the visual stimuli were replaced by the auditory stimuli of Experiment 2. Tone frequency, which was irrelevant in Experiment 2, now specified the target force level, whereas intensity was irrelevant. The larger auditory compatibility effect as compared to the visual effect (Experiments 1 to 4) suggested that there is a stronger correspondence between auditory stimuli and response force than between visual stimuli and response force. If the irrelevant dimension of stimulus intensity induces automatically equivalent codes, one should expect a more pronounced intensity–force compatibility effect with auditory stimulation.
Method

Participants, stimuli, and procedure

As in Experiment 2, tones with frequencies of 800 and 1200 Hz and intensities of 50 and 70 dB(A) were employed. The sound intensity as the energy-related stimulus feature of interest was task irrelevant this time. Participants were required to choose the response force level according to the pitch of the stimulus. The procedure was identical to that of Experiment 5.

Results

The average force levels for weak and strong responses were 245 and 1456 cN, respectively.

Response errors. There were 0.8% premature responses (<100 ms) and 1.2% slow responses (>1000 ms). The errors of incorrect response force again revealed a significant compatibility effect, indicated by the interaction of stimulus intensity and force level, $F(1, 19) = 12.4, p < .01$. Incorrect response force was produced in 1.9% of the corresponding responses and in 3.2% of the non-corresponding responses.

Reaction time. The right panel of Figure 2 depicts mean RT as a function of stimulus intensity and force level. Force level revealed a highly significant main effect, $F(1, 19) = 76.5, p < .001$, with mean RTs of 454 and 380 ms for weak and strong keypresses, respectively. As in Experiment 5, the two sound intensities did not produce significantly different RT’s, $F(1, 19) = 1.3, p > .2$. Most important, there was a significant interaction between the two factors, $F(1, 19) = 22.8, p < .001$. Corresponding responses were again faster than non-corresponding responses (407 vs. 428 ms).

Discussion

In this experiment responses were faster when the irrelevant intensity of the stimulus corresponded to the force level of the response than when these two dimensions did not correspond. As expected, this 21-ms compatibility effect was larger than the 8-ms effect of Experiment 5, $t(38) = 2.3, p < .05$. This increased effect for the auditory modality compared to the visual modality suggests once more that more effective codes are generated for auditory than for visual stimuli. This pattern of results also indicates that the same intensity codes are formed within each sensory modality, whether or not stimulus intensity is relevant for performing the task.

GENERAL DISCUSSION

The experiments reported in this article sought to refine the interpretation of the intensity–force compatibility effect originally reported by Romaiguère et al. (1993). These authors reported that responses were carried out faster when a bright stimulus called for a strong thumb press and a dim stimulus for a weak thumb press than when this S–R assignment was reversed by the instruction. They attributed this compatibility effect to symbolic S–R transformation processes.
The present paper addressed the theoretical question as to whether the codes involved in intensity-to-force translation are codes for the higher linguistic categories (large and small) or whether the codes are analogue representations reflecting the physical and sensory properties of the stimulus. According to the linguistic code assumption, the size of the compatibility effect should be modulated neither by intensity manipulations nor by changes of sensory modality. In contrast, analogue codes imply that such factors should influence the size of the effect.

Experiment 1 was mainly a replication of the original study and served as a baseline for the other experiments. As in the study of Romaiguère et al. (1993) weak responses to dim stimuli and strong responses to bright stimuli were carried out faster than when the assignment of stimulus intensity to target force level was reversed. Experiment 2 generalized this effect to auditory stimuli. The effect was larger than that obtained with visual stimuli. Experiment 3 employed visual stimuli with a largely increased intensity difference (29.1 dB), and Experiment 4 employed auditory stimuli with a largely decreased intensity difference (10.0 dB). The pattern of results of these four experiments showed that the compatibility effect is larger for auditory than for visual stimuli whereas intensity differences exert virtually no effect. Experiments 5 and 6 demonstrated that a compatibility effect is also obtained when intensity is a task-irrelevant dimension of the visual and the auditory stimuli, respectively. Again, the effect was larger for auditory than for visual stimuli.

As mentioned before, auditory stimuli produced larger compatibility effects (Experiments 2, 4, and 6) than did visual stimuli (Experiments 1, 3, and 5). On the other hand, changes of intensity within each modality produced only small and unreliable changes of the compatibility effect. Although the dB difference between the high and low intensity was almost doubled within each modality (15.5 vs. 29.1 dB with visual stimuli and 10.0 vs. 20.0 dB with auditory stimuli), the compatibility effect was not significantly different in either case. On the other hand, intensity–force compatibility depended strongly on the sensory modality.

The finding that compatibility depends on physical properties—whether it is stimulus modality or stimulus intensity—provides evidence against the linguistic coding hypothesis. Additionally, the findings of Experiments 5 and 6 provide further evidence against the hypothesis that the compatibility effect is based on linguistic labels. In these experiments the task-relevant attribute was either the geometric shape of a visual stimulus or the pitch of a tone. If linguistic labels are formed to solve the task, it is essential that stimuli are coded in terms of the relevant stimulus dimension and not in terms of task-irrelevant stimulus attributes. Therefore, it appears unlikely that high-level linguistic labels were effective in producing the intensity–force correspondence effects in Experiments 5 and 6.

The conclusion that stimulus intensity codes are automatically formed and influence the coding of response force also contributes to the interpretation of studies that examined the influence of stimulus intensity on response force in RT paradigms (Angel, 1973; Jaskowski et al., 1995; Miller et al., 1999; Ulrich et al., 1998). In these studies, response force was not constrained within certain target ranges but was simply measured as a dependent variable in addition to RT. The findings of these studies can be summarized as follows. First, response force increases with stimulus intensity, and, second, this effect is more easily obtained or more pronounced with auditory than with visual stimuli (cf., Ulrich et al., 1998). Ulrich and Mattes (1996) have suggested that participants code the intensity of a visual warning signal and that this somehow influences the force output. The present findings support this coding interpretation of response force effects.
The analogue coding hypothesis assumes that codes, which reflect the physical properties of the stimulus, are involved in the S–R translation. Accordingly, this hypothesis can account for the present finding of a larger compatibility effect for auditory than visual stimuli but not for the missing effect of intensity changes within modalities. Therefore, the present finding raises the question of why modality influences intensity–force compatibility so strongly whereas substantial changes of stimulus intensity did not produce significant effects. We now discuss the nature of the codes that may be employed in the S–R translation process and may have produced this pattern of results.

Modality-specific stimulus representations

One cognitive explanation proceeds from the assumption that the stimulus–response mapping is coded in an auditory representational system like, for example, the phonological loop of the working-memory model by Baddeley (1986). Recent work by Adam et al. (1998; see also Kleinsorge, 1999) provides evidence that participants prefer to employ verbal response mapping rules with orthogonal S–R assignment (e.g., up–left/down–right) unless experimental manipulations suggest other representational modes of S–R mapping. For the present study, the difference between auditory and visual stimuli would then be that auditory stimuli are transformed within the same subsystem, whereas visual stimuli have to be transformed from a visual subsystem to the phonological one. The additional transformation steps might diminish the size of the compatibility effect.

Perhaps a simpler account of the present finding is provided by the salient-feature coding hypothesis (cf., Proctor et al., 1992). This hypothesis states that S–R translation is more efficient when the salient features of the stimulus and the response correspond than when they do not. Accordingly, one might assume that coding of stimulus dimensions in vision and audition is asymmetrical, with a loud tone providing the polar referent most closely matching that for the response dimension (strong response). In contrast, the visual code for bright must be assumed to be less salient thereby producing a less strong match with the response code. This view accords with present findings of modality-specific influences on the size of the intensity–force compatibility effect. In addition, one might assume that changes of stimulus intensity within modalities are also associated with changes in stimulus saliency. Accordingly, such stimulus intensity changes could change the force compatibility effect as well. This assumption found little support in the present experiments, because changes of stimulus intensity within each modality did not reliably change the intensity–force compatibility effect. It should be noted, however, that the salient-feature principle is relatively vague as to the ways saliency is derived for a specific stimulus. As a result, the observed absence of within-modality changes of the intensity–force compatibility effect does not necessarily speak against this hypothesis.

Action effects

A quite different yet interesting explanation for the modality differences can be derived from findings that demonstrated an influence of learned action effects on performance (Elsner & Hommel, 2001; Hommel, 1996; Kunde, 2001). Kunde demonstrated influences of action effects on performance in a task in which participants were asked to produce either strong or weak responses that were immediately followed by an auditory signal of varying intensity. In corresponding response–effect blocks, strong responses were followed by a loud tone and
weak responses by a soft tone. In non–corresponding response–effect blocks, the response–effect assignment was reversed. Most interesting was that RT was shorter in corresponding than in non–corresponding blocks, which led Kunde to suggest that anticipatory effect representations become effective in response selection. Similar to the study of Kunde, in the present experiments, the response was either a weak or a strong keypress except that the keys employed produced no sound at all. But nevertheless, in the auditory experiments there might have been a strong correspondence between the stimuli and the lifelong learned effect of the action, because in many everyday situations more force goes with a loud sound and weak force with a soft sound (e.g., typing on a keyboard or knocking on a table). On the other hand, for visual stimuli there seems to be no such correspondence. This can explain why the intensity–force compatibility effect was stronger for auditory than for visual stimuli. It should be mentioned, though, that such action–based considerations are not meant to replace the usual coding explanations of S–R compatibility but rather to supplement them (cf., Hommel, 1996; Tucker & Ellis, 1998).

In conclusion, the present study demonstrated that the well–known phenomenon of stimulus–response compatibility is also present when stimuli and responses vary along different physical dimensions (e.g., brightness vs. force) and that these effects are also obtained when stimulus intensity is task irrelevant. It remains, however, an open question why intensity–force compatibility is clearly stronger for auditory than for visual stimulation. We have discussed differences in the representational mode and accounts based on action effects as possible sources of this asymmetry. Research designed to clarify this issue should certainly contribute further to a better understanding of the phenomenon of stimulus–response compatibility.

REFERENCES


4Furthermore, this explanation seems to be in accordance with the observation that some participants spontaneously reported that the incompatible condition had felt “very odd” with auditory stimuli, whereas no such reports were made after the experiments with visual stimuli. These introspective reports might reflect the learned relation between manual action and sound.


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