On the translation of some stimulus features to response force

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Abstract. Romaiguère et al. (1993) reported an stimulus-response (S-R) experiment in which the participants had to respond to bright or dim stimuli by pressing a key strongly or weakly. Reaction time (RT) for a compatible S-R assignment (bright-strong; dim-weak) was substantially shorter than for an incompatible S-R assignment (dim-strong; bright-weak). This effect was explained as a direct translation of stimulus intensity to response force (RF). In the present study, we looked for other stimulus features that could be directly transferred to RF. We investigated stimulus size (large/small), vertical location (above/below), and brightness (bright/dim). Delays of RT for incompatible trials were found in case of brightness and size, but not location. In a second experiment, we tested whether such a direct translation might even cause changes of spontaneous RF. Without being instructed about RF, participants made simple reactions to stimuli which differed either in location, size or brightness. Indeed, stimulus size affected RF: larger stimuli were associated with stronger responses. In contrast, brightness had no effect. Thus, we replicated and extended Romaiguère et al.'s (1993) finding. However, the direct-translation account for RF variations received only partial support from our data.

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INTRODUCTION

Angel (1973) was the first to show that stimulus intensity affects not only the speed but also the force of responses: independently of stimulus modality (visual, auditory or tactile), the more intense the stimuli were, the stronger were the responses. Since Angel's study, this finding was replicated more or less successfully several times. The effect appears to be quite robust for auditory stimuli (Jaśkowski et al. 1995, Miller et al. 1991, Ulrich et al. 1998) but is rather variable for visual stimuli (Jaśkowski et al. 1995, Miller et al. 1991, Ulrich et al. 1998). This pattern of results may reflect the impact of transient arousal. Arousal is understood "as a general state of central nervous activity" (Robbins and Everitt 1995, p. 703) which is related to other constructs of energetizing performance like drive or motivation. Although the concept of arousal is unclear (Robbins and Everitt 1995) both in psychological and in neuroscientific terms, it is commonly accepted that fluctuations in arousal level are modulated by nonspecific aspects of stimulus input, like intensity and salience. In particular, it is commonly believed that more intense auditory (but not visual) stimuli induce a phasic state of higher arousal, which facilitates processing, although there is no agreement as to how general is the effect of arousal (cf. Nissen 1977, Sanders 1983).

Ulrich and Mattes (1996) investigated more systematically the effect of transient arousal on response force. Transient arousal was manipulated by varying the intensity, modality, and temporal interval of a warning signal which closely preceded the imperative stimulus. Participants responded more strongly after loud than after soft warning signals. However, response force was also larger after bright than after dim warning signals although visual intensity is not considered to affect arousal. Moreover, independently of the modality of warning stimuli, this intensity effect on response force remained constant over a wide range of different foreperiods, in contrast to the notion of a decaying effect of transient arousal. Therefore, Ulrich and Mattes rejected the hypothesis that arousal mediates the effect of intensity on response force and proposed a "stimulus-response compatibility hypothesis" instead.

Stimulus-response (S-R) compatibility is one of the most intensively investigated problems of cognitive psychology (e.g., Kornblum et al. 1990). Its mechanisms have been studied most commonly when stimuli and responses vary on the left-right dimension. Two modes of functioning have been demonstrated (de Jong et al. 1994, Wascher et al. 2001): one mechanism decays over time and has its effects only when responses are "natural" (i.e., hands are not crossed) and when stimuli are easy to localize (i.e., in the visual modality). Wascher et al. (2001) identified this mechanism as intrahemispheric transfer of activation from perceptual to motor areas. The other mechanism does not decay over time and is relatively independent of any "natural" arrangement of responses and stimuli. This mechanism appears to reflect a common code (see e.g., Hommel 1996, Hommel et al. 2001, Kornblum et al. 1990, Müsseler 1999, Wascher et al. 2001) used by participants to represent the features of stimuli and responses.

Thus, when referring to "S-R compatibility" to account for a non-decaying effect independent of arousal, Ulrich and Mattes (1996) obviously were specifically referring to the portion of the S-R compatibility effect that is best explained by common cognitive codes. Indeed, they suggested that "subjects code the intensity of the visual signal as weak or strong and assimilate the level of force output with the coded intensity level" (Ulrich and Mattes 1996, p. 987). In contrast, the portion of the S-R compatibility effect that is best explained by intrahemispheric spread of activation bears some resemblance to the possible effects of arousal on peak force, both decaying over time and both being related to specific features of stimulation.

More generally, the introduction of the "S-R compatibility" terminology to research on response force is interesting for two reasons: it may help to explain variations of response force, as intended by Ulrich and Mattes. On the other hand, the response force perspective on S-R compatibility, if further elaborated, might also be useful in generalizing the conception of S-R compatibility which has been discussed until recently with only response speed and response errors as dependent variables. The quality of a given response, as might be reflected in parameters of force development over time, has remained unexamined. An important step in this second direction was a study by Romaiguère, Hasbroucq, Possamaï and Seal (1993) describing an effect of compatibility between stimulus intensity and response force that was reflected in response times. In one block participants had to press strongly to bright stimuli and weakly to dim stimuli, and vice versa in the other block. Responses were faster by about 25 ms in the former than in the latter block, obviously because the mapping bright-strong, weak-dim was more compatible than the reversed mapping. In a similar vein, Grosjean

and Mordkoff (2001) instructed participants in one block to hold down a key for a long time to long stimuli and for a short time to short stimuli (compatible situation), and the reverse in the other block (incompatible). Response times were drastically longer in the incompatible situation, by about 300 ms. The results of Romaiguère et al. (1993) were recently successfully replicated by Mattes, Leuthold and Ulrich (2002)

One account of these results is by reference to a common cognitive code for stimulus and response: in the compatible case of the Romaiguère et al. study (1993), participants might have translated the rule to press forcefully to the bright stimulus and weakly to the dim one to the common code of pressing intensively to the intensive stimulus and weakly to the weak stimulus.

The notion of a common framework for perceptual and action codes dates back to Greenwald (1970) who pointed out that such an overlapping could be a quite natural effect of resemblance of stimuli and their perceivable consequences. If an observer perceives a stimulus that resembles the effects of a certain action, the code of this action is activated. This idea was developed by Prinz (1990, 1992) and was recently summarized in the theory of event coding (TEC, Hommel et al. 2001). Prinz and his coworkers reject a strict separation between perception and action assuming that they both operate on the same neural representations. In other words, if a code is activated, it is activated both for perception and for action. This leads to the prediction that if a stimulus activates some perceptual code which is also necessary to represent the response to this stimulus, the response is facilitated because this specific code is primed in advance. TEC could successfully explain Romaiguère et al.'s (1993) finding. Indeed, assuming that stimulus intensity calls for the same mental representation as the response-force level, an increase in stimulus intensity should result in a stronger activation of the code for the level of response force. Therefore, the stronger response is facilitated.

In the present experiments we tried to replicate and extend the effect observed by Romaiguère et al. (1993) and to test Ulrich and Mattes' (1996) hypothesis. The logic of this attempt is as follows. In Experiment 1, we investigated whether there are other stimulus features in addition to visual intensity which produce the effect observed by Romaiguère et al. We replicated Romaiguère et al.'s variation of visual intensity and extended it to test additional dimensions, two in the visual and one in the auditory domain. We followed the rationale used by

Romaiguère et al.: if the instruction to press strongly to one stimulus and weakly to the other one would yield faster responses than the opposite assignment then this would be evidence for compatibility. In Experiment 2, we followed Ulrich and Mates' reasoning: assuming that there is a Romaiguère et al.-like S-R compatibility for a given dimension, we expected spontaneous variation of response force in the simple reaction-time task for this dimension. Thus, we again presented stimuli varying on these dimensions but requiring no choice (forceful vs. weak) responses. Rather, simple responses were required, without any instruction about force, and the question of interest was whether the variation of the stimuli would lead to "spontaneous" variation of response force.

EXPERIMENT 1

We adapted Romaiguère et al.'s (1993) task in which subjects were to respond with two different levels of force to two different stimuli varying in their visual intensity and extended this approach to test two additional stimulus dimensions: size (large vs. small) and location (above vs. below center). If the instruction to press strongly to one stimulus and weakly to the other one would yield faster responses than the opposite assignment then this would be evidence for compatibility. To state the rationale of common coding explicitly: the question was whether participants would do the following translations, in addition to the one described in the Introduction for brightness. For size: translate the rule to press forcefully to the large stimulus and weakly to the small one, to the common code of pressing much to the large stimulus and only a little bit to the small one. For location: translate the rule to press forcefully to the upper stimulus and weakly to the lower one, to the common code of exerting higher pressure to the higher stimulus and lower pressure to the lower one. When stimulus-response mapping would be reversed, these codes would be expected to impair speeded responding. Thus response times were expected to be delayed compared to the other mapping.

Method

Subjects

Twelve right-handed participants (9 female and 3 male) whose ages were between 17 and 32 years

(mean = 23, SD = 3.7), with normal or corrected-to-normal visual acuity and with normal hearing participated in the experiment. All participants were naive about the purposes of the experiment and were paid 25 DM for their participation.

Stimuli

Stimuli were white shapes presented on the black background of a monitor screen driven by a PC. Their luminance was 38.3 cd/m^2, except as noted below for the brightness condition.

Each trial started with the display of a small red fixation cross in the middle of the screen, which remained there until 500 ms after participants' response. Participants were asked to fix their gaze on the cross during a trial. The length of the period between cross presentation and the imperative stimulus was a sum of a constant interval of 700 ms and an interval sampled from an exponential distribution with a mean of 700 ms. The next trial started 1.5 s after fixation cross offset.

Each session was divided into 6 blocks. Within each block the stimuli differed on one of the following features.

Stimulus location. On each trial a filled rectangle (1.1° × 1.2°) was presented either above or below the fixation cross. The distance between the inner edge of the rectangle and the center of the fixation cross was 2.6°.

Stimulus size. On each trial, a ring was displayed, concentric with the fixation cross. Line width was 1 pixel. The radius was either 2.5° or 0.7°.

Stimulus brightness. On each trial, a filled rectangle (1.1° × 1.2°) was presented in the center of the computer monitor. It was either bright (132.7 cd/m^2) or dim (2.5 cd/m^2).

Force recordings

Force changes were recorded by a special isometric key with two built-in extensometers embodied in a bridge. The output signal from the bridge was sent *via* a 12-bit A/D converter to a 486/DX compatible computer. The signal was digitized at a rate of 200 samples/s.

Procedure

Participants were seated in a comfortable armchair in a darkened and sound-proof chamber in front of the computer screen. The observation distance was 125 cm. Two response keys were mounted on the arms of the

chair and subjects were asked to respond by pressing with their dominant hand the key which was positioned on the same side. Participants were free to use index fingers or thumbs but they had to use the same finger in the entire session. Furthermore, they were told to leave their fingers on the response key during the measurements.

Unlike in Romaiguère et al.'s study (1993), the force which participants had to exert on the response key was not defined according to any preset criterion: participants were asked to generate a force which was strong or weak according to their own judgment.

Each block contained 80 trials, with 40 trials of either type of stimulus (e.g., large and small) presented in an unpredictable order. For each of the three stimulus dimensions, there was one "compatible" and one "incompatible" block. In blocks with a compatible assignment, the participants' task was to produce a strong press in response to a "strong" stimulus (above center, large, bright) and a weak press in response to a "weak" stimulus (below center, small, dim). In incompatible blocks the assignment was reversed. The order of the blocks was randomized. The session lasted for about 70 minutes.

Data Analysis

Two dependent variables were measured: reaction time and peak force. Reaction time was defined as the time until the force exerted on the key became equal to 2 N[1]. Peak force was the highest value of the force-time function.

To evaluate the statistical significance of the results, three-way analysis of variance with three within-subjects factors was used: stimulus dimension (location, size and brightness), S-R assignment (compatible vs. incompatible) and type of required response (strong vs. weak). If necessary (in case of effects of the 3-level factor of stimulus dimension), the degrees of freedom were corrected by using Huynh-Feldt coefficients.

Results

Peak force

Peak force was affected by required force, being larger in trials that called for strong than for weak responses (22.8 N vs. 5.9 N, $F_{1,11}$=47.6, P<0.001). Al-

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[1]N (Newton) is a unit of force. 1 N is equivalent to a force that gives a mass of 1 kg an acceleration of (kg × m)/s^2.
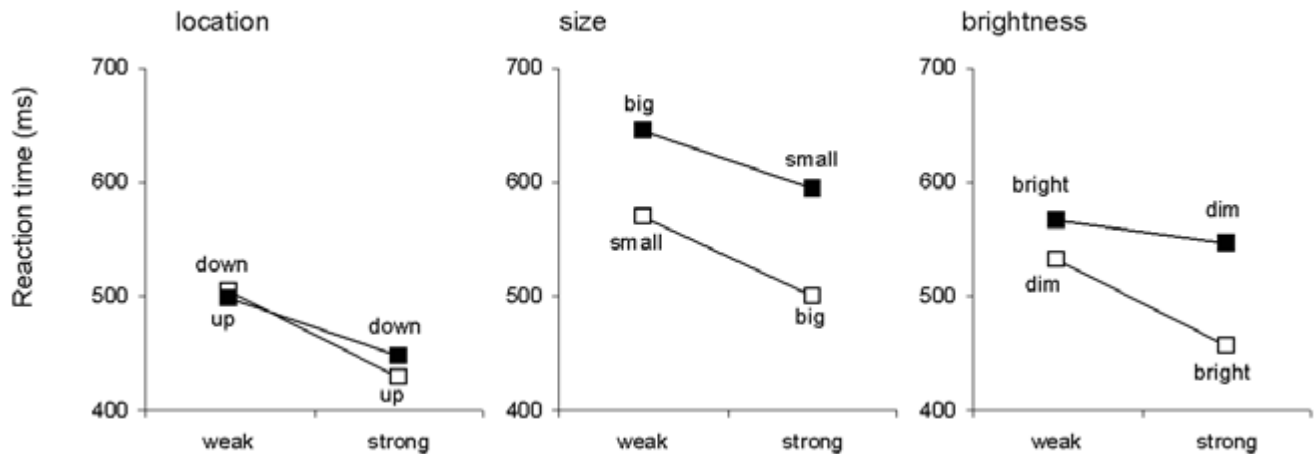
Fig. 1. Reaction times from Experiment 1 for weak- and strong-required responses for the different stimulus dimensions. Filled squares denote results for "incompatible" trials and open squares denote results for "compatible" trials.

though trivial, this result indicates that participants generally followed the experimental instruction. This effect did not interact with stimulus dimension ($F_{3,33}$=2.52, P=0.088) nor was any other significant effect.

Reaction time

Mean reaction times are plotted in Fig. 1. All main effects turned out to be significant. Reaction times were shorter in compatible than in incompatible trials (498 vs. 550 ms; $F_{1,11}$=8.31, P=0.015), were shorter for strong-required responses than for weak-required responses (495 vs. 552 ms; $F_{1,11}$=27.9, P<0.001) and differed between dimensions ($F_{2,22}$=17.5, P<0.001). The compatibility effect was weaker for weak-required force (35 ms) than for strong-required force (67 ms) as indicated by interaction between compatibility and required force: $F_{1,11}$=8.8, P=0.013. Of main interest, the compatibility × dimension interaction was marginally significant ($F_{2,22}$=3.20, P=0.060). Additional two-way ANOVAs were performed separately for each dimension to explain this interaction. Significant effects of S-R assignment, with RTs being shorter for compatible than for incompatible trials, were found for stimulus size (535 vs. 620 ms, $F_{1,11}$=13.0, P=0.004), for brightness (494 vs. 557 ms, $F_{1,11}$=6.0, P=0.033) but not for stimulus position ($F_{1,11}$=0.57).

Discussion

We successfully replicated and extended Romaiguère et al.'s (1993) finding that when assigning the strong re-

sponse to the bright stimulus and the weak response to the dim stimulus, RTs were shorter than with the reversed assignment. This replication was obtained although in the original experiment by Romaiguère et al. participants were trained before the session to keep strong and weak response force in given limits, whereas in our experiment, participants were free to choose the force to make strong and weak responses. Nevertheless, the difference of 58 ms obtained in the present study between compatible and incompatible assignment of responses to bright and dim stimuli was certainly not less than the difference of about 25 ms obtained by Romaiguère et al. (1993).

Moreover, we obtained a result similar to the brightness variation when varying size of a visual stimulus: with the assignment large stimulus – strong response and small stimulus – weak response, RTs were shorter than with the reversed ("incompatible") assignment.

The size effect was brought about by displaying thin rings varying in diameter. It is extremely improbable that the larger ring was evoking more transient arousal than the smaller one. Therefore the size effect is most probably brought about by a common code, i.e., the large/small stimulus variation and the strong/weak response variation are coded by participants in a common scale, facilitating strong responses to large stimuli and weak responses to small stimuli. By inference, the brightness effect was also, to some degree, due to such common coding.

EXPERIMENT 2

In this experiment, stimuli again varied in each block between two values of a given dimensions but choice re-

sponses (forceful vs. weak) were no longer required. Rather, simple responses were required, without any instruction about force, and the question of interest was whether variation of stimuli would lead to corresponding "spontaneous" variation of response force. Thus, unlike Experiment 1, variation in stimulus dimensions was task-irrelevant. Any effects of these variations on response force would therefore indicate a certain degree of automaticity of these effects. On the basis of the results of Experiment 1, we expected that brightness and size, but not location, should affect spontaneous response force in this simple RT experiment. Therefore, we predicted that participants would respond more forcefully to brighter and larger, but not to stimuli presented above (vs. below) fixation.

Method

Subjects

A fresh sample of 19 (mean = 22, SD = 3.2) right-handed participants was recruited. All had normal or corrected-to-normal visual acuity and normal hearing. All were naive about the purposes of the experiment. In particular, they did not know that response force was the variable of interest.

Apparatus and Stimuli

We used the same pairs of stimuli as in Experiment 1. Physical characteristics and timing of the stimuli and the apparatus were the same as in Experiment 1.
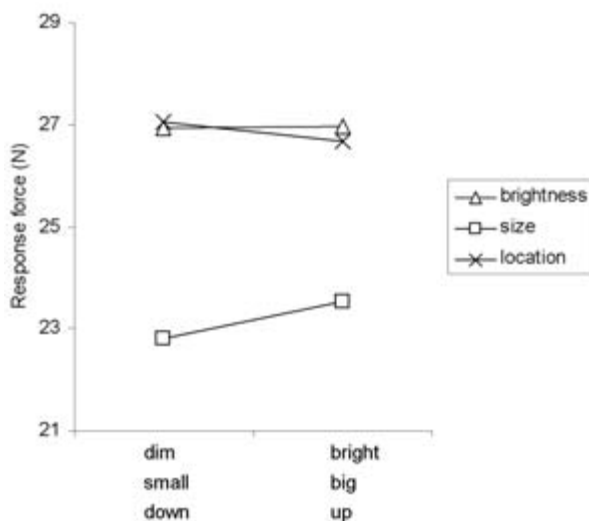

Fig. 2. Response force (RF) measured in Experiment 2 as a function of stimulus type.

Procedure

There were 3 blocks of 120 trials. In each block, stimuli of one type (bright/dim, large/small, and above/below) were presented in random order. The participants' task was to press the response key as soon as possible to each detected stimulus.

Statistical evaluation

A repeated measures ANOVA with the two factors of dimension (location, size, brightness) and level ("low": below, small, dim *versus* "high": above, large, bright) was performed to determine statistical significance of the data.

Results

Peak force

Peak forces are depicted in Fig. 2. Peak force seemed to be smaller for size than for the other two dimensions (Fig. 2). But because of relatively large between-blocks variability no general difference in PF between the responses to the three dimensions was found ($F_{2,36}$=1.57, P=0.238). Peak force was also independent of stimulus level ($F_{1,18}$=0.645, P=0.432). However, the interaction was significant ($F_{2,36}$=3.76, P=0.033). As follows from additional ANOVAs performed separately for each dimension, this is because there was no effect of level with brightness and location while a significant effect was found in case of size: peak forces were stronger for large than for small stimuli (23.5 vs. 22.8 N, $F_{1,18}$=4.8, P=0.041).

Reaction time

RTs were shorter for the "high" than for the "low" level (263 vs. 276 ms, $F_{1,18}$=38.4, P<0.001). Moreover, the interaction was significant ($F_{2,36}$=13.9, P<0.001). One-way ANOVAs performed separately for every dimension indicated that this was because participants were faster for the bright than for the dim stimuli (253 vs. 278 ms; $F_{1,18}$=95.7, P<0.001) and for the large than for the small stimuli (264 vs. 274 ms; $F_{1,18}$=8.1, P=0.010) but not for upper vs. lower stimuli.

Discussion

The pattern of results on peak force was more complex than expected: While size was indeed found to affect

spontaneous response force in this simple RT task according to our predictions, brightness had no effect. We will come back to this problem in the General Discussion.

The results for reaction time are surprising. While the effect of brightness on RT is plausible, because responses are, as a rule, faster when stimuli are more intense (e.g., Mansfield 1973), the effect of size is counterintuitive. With respect to size, one would have rather expected short RT for smaller rings because the smaller ring is a more foveal stimulus than the larger ring (Payne 1966, 1967, Rains 1963). Thus, there must be a process working against this tendency, speeding responses to the larger object. Above, when discussing the results of Experiment 1, we had discarded the possibility that the larger and smaller rings might differ in the evoked transient arousal. We had constructed these stimuli by varying the diameter of a thin ring to exclude variations in arousal as much as possible. However, if the larger ring would nevertheless evoke some more arousal then this would account for the effect of size on RT. Sanders (1975, Sanders and Wertheim 1973) and Niemi (1979, Niemi and Lehtonen 1982, Niemi and Näätänen 1981) tried to manipulate arousal level by changing physical parameters (intensity or/and size) of a warning signal which closely preceded an imperative stimulus. They argued that a physical parameter affected arousal if its effect on RT was larger for short than for long foreperiods, because stimulus-induced transient arousal is expected to decay over time. Sanders (1975) found no arousing effect of much brighter visual stimuli than ours with a size of 1°10'. Nevertheless the possibility that our large stimuli might have evoked more arousal than small ones cannot be excluded as the effect of stimulus size on transient arousal has so far not been systematically investigated (see Niemi and Lehtonen (1982) who showed an arousing effect of visual stimuli with size of 7° and luminance of 34 cd/m^2). Recent results of Jaśkowski and Włodarczyk (submitted) support this idea. Comparing RTs and RFs between small and large targets as a function of brightness, they found that participants' simple responses were faster to large than to small targets by 12 ms on average. However in all these studies that varied stimulus size, filled shapes were used as targets, not rings as in this study.

GENERAL DISCUSSION

In Experiment 1, we replicated Romaiguère et al.'s (1993) result that when assigning the strong response to the bright stimulus and the weak response to the dim stimulus, RTs were shorter than with the reversed assignment. The effect amounted to 63 ms. Extending Romaiguère et al.'s (1993) findings, we obtained similar RT results when varying the diameter of a thin ring. Again, RTs were shorter when assigning the strong response to the large stimulus and the weak response to the small stimulus than with the reversed assignment. The effect amounted to 85 ms. For the other investigated dimension, location, such S-R compatibility was not found.

In Experiment 2, spontaneous variations of response force were found for variations of stimulus size: without being given any instruction about force, participants responded more forcefully to the larger than to the smaller ring and also responded faster to the larger ring. In contrast, there were no variations of force in response to bright vs. dim stimuli (nor to upper vs. lower stimuli) although participants also responded faster to bright than to dim stimuli. Table 1 summarizes these results.

The common coding hypothesis does not have particular problems in accounting for the results of Experiment 1: "bright" and "forceful" might share the code "intensive" with each other, likewise "large diameter" and "forceful" might share the code "big". Thus, there is S-R compatibility with those pairings, due to common codes. Correspondingly, *post-hoc*, it is plausible to assume that there is no privileged association between "forceful" and either "upper" position or "lower" position, accounting for the result that no S-R compatibility was found for the dimension of location. We had expected that participants might associate "high pressure" to "high position" but since keys were pressed by exerting force downwards, "high pressure" might as well be associated to "low position".

However, it is hard to understand on the basis of the common-coding hypothesis why variations of size had

Table I

Summary of effects in experiments 1 and 2

	Brightness	Size	Location
Exp.1: RT*	+ (63 ms)	+ (85 ms)	n.s.
Exp.2: RF[#]	n.s.	+ (1.3 N)	n.s.
RT[#]	+ (25 ms)	+ (≥ 10 ms)	n.s.

(*) Effect of compatibility; ([#]) Effect of high level vs. low level

effects on spontaneous force in Experiment 2. In analogy to the effects of left-right compatibility, which have been found to be massively reduced in simple responses, no effect of the present "large-forceful" compatibility was to be expected with simple responses, simply because there is no need to form this code for responding (cf. Hommel 1996, Kornblum et al. 1990). In agreement with these considerations, there was no effect of the brightness variation on response force anymore. In contrast to these considerations, however, there was a reliable effect of the size variation on response force. It is not clear on the basis of the common coding hypothesis why there was an effect with variation of the one dimension but not of the other.

The arousal hypothesis has problems accounting for the main results of Experiment 1: the luminance difference between the bright and dim stimuli (133 vs. 3 cd/m^2) was considerably smaller than luminance differences that would usually result in measurable changes of arousal, as measured by Sanders (1975). Likewise the variation of the diameter of the thin ring from 0.7° to 2.5° was not expected to result in any changes of arousal as measured by response force (Jaśkowski and Włodarczyk, submitted). Likewise, no effects on arousal were expected for variations in the upper vs. lower location, an expectation supported by the results. Thus, on the basis of arousal, there was no justification for defining one instruction as compatible and the other as incompatible. Nevertheless, clear effects of the compatibility variation were obtained. For argument's sake, one might suppose that the brightness variation did have effects on arousal. Then the less "natural" way of responding strongly to dim stimuli and weakly to bright stimuli might fit this notion. But then a mechanism different from arousal has to be assumed to explain the size variation.

Unlike the common-coding hypothesis, the arousal hypothesis has no principal problems accounting for the effects of intensive stimuli on the force of simple responses as investigated in Experiment 2, due to the assumed tight coupling between stimulus-induced arousal and response-related activation in simple-response tasks (Sanders 1983). However, the particular pattern of results obtained in Experiment 2 was paradoxical. Response force was not affected by brightness, unlike Experiment 1, but was affected by size. It is not clear on the basis of the arousal hypothesis why there was an effect of variation of the one dimension but not of the other.

Thus, neither of the two hypotheses can account for the complete pattern of results.

CONCLUSIONS

We replicated and extended Romaiguère et al.'s (1993) finding: besides brightness, size also showed marked S-R compatibility effects with response force, as measured by response times to compatible and incompatible pairings. Furthermore, stimulus size affected spontaneous response force. Neither the common-coding nor the arousal hypotheses were able to provide a comprehensive account of this pattern of results.

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