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Mini review

Stimulus coding in human associative learning: Flexible representations of parts and wholes

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Abstract

An enduring theme for theories of associative learning is the problem of explaining how configural discriminations—ones in which the significance of combinations of cues is inconsistent with the significance of the individual cues themselves—are learned. One approach has been to assume that configurations are the basic representational form on which associative processes operate, another has tried in contrast to retain elementalism. We review evidence that human learning is representationally flexible in a way that challenges both configural and elemental theories. We describe research showing that task demands, prior experience, instructions, and stimulus properties all influence whether a particular problem is solved configurally or elementally. Lines of possible future theory development are discussed.

Keywords: Associative learning; Configural; Elemental

A fundamental issue in learning theory is the part/whole problem. In any situation in which a stimulus has useful predictive value, that stimulus is embedded within an array of other stimuli, at the very least those which comprise the learning context. Hence a basic question which theorists have grappled with for decades is whether learning attaches independently to the elements which constitute the entire sensory array or whether it attaches instead to that array as a whole. Theories which adopt the former view, so-called 'elemental' theories, assume that responding to an array composed of many elements is a direct function of the values attached to the elements themselves, with the whole array having no separate value over and above that of its constituent parts. In contrast, theories which assume that the basic units of learning are entire arrays ('configural' theories) assume that responding is driven by knowledge about the whole array, independently of what its parts may signify.

Although there has been a rich and productive history of research on the part/whole or elemental/configural issue (Baker, 1968; Kehoe and Gormezano, 1980), most current theories of associative learning assume that stimuli are invariably processed in one and the same way. To state the obvious, configural theories (e.g., Pearce, 1987, 1994) account for the many and varied phenomena of learning in terms of configural representations, while elemental theories (e.g., Harris, 2006; Rescorla and Wagner, 1972) do so in terms of elemental coding. As a consequence, the question of whether stimuli are processed elementally or configurally is usually discussed in an either/or manner (see Pearce and Bouton, 2001; Wasserman and Miller, 1997, for reviews). But a number of studies conducted over the past few years have suggested that the way in which stimuli are processed is not fixed: instead, it can be profoundly influenced by a range of factors. This finding, first reported in animal conditioning by Alvarado and Rudy (1992) and subsequently observed in human learning, represents a major challenge to current learning theories. The aim of the present article is to review and summarize this work in the context of human associative learning and to try to extract the major factors which influence the elemental/configural balance. In addition, we present several theoretical ideas that have been suggested to allow for flexibility in part/whole coding, and we also review models with hidden units that can adapt themselves dynamically depending on whether an elemental or a configural representation is more useful in solving a task (e.g., Schmajuk and DiCarlo, 1992). Our hope is that this review will provide some focus for future theoretical developments.

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Traditionally, many well known effects in the field of associative learning have been successfully explained in an *elemental* manner (Wagner, 1971) whereby it is assumed that stimulus components are represented as separate entities and that the overall associative strength of a configuration or compound is based on the algebraic sum of the associative strengths of its components. This elemental summation principle is incorporated into many theories of associative learning (e.g., Mackintosh, 1975; Pearce, 1987; Rescorla and Wagner, 1972). It is formally stated in Eq. (1):

$$V_{\mathrm{CS}} = \sum\nolimits_i V_i, \tag{1}$$

where V_{CS} is the overall associative strength of a conditioned stimulus (CS) and V_i the associative strength of the ith component. This summation principle has two important consequences. First, it predicts that when two separately trained stimuli are presented together, responding to this compound will be more pronounced than to either element alone, a phenomenon called summation. And second, it assumes that the total associative strength of a CS is distributed among several components. Yet, in some situations it may be distributed rather unequally among the different components. As a consequence, the major amount of associative strength supported by a reinforcer or outcome may be held by one component at the expense of other components. This property of elemental theories can explain a class of selective learning phenomena collectively referred to as cue competition effects.

On the other hand, however, there is considerable evidence that humans as well as animals can successfully handle discrimination problems that cannot be solved elementally. Therefore, some authors have suggested instead that stimuli are commonly processed *configurally*. The strongest claim about how such a configural representation might be formed is that a compound maps onto a representational entity that is distinct from its elements and that it is only this entity that enters into an association with the outcome. This means, for example, that a compound consisting of two components, say A and B, is processed and represented with no relation to its components but as a unique configuration instead (call it X). This would be a purely configural view. A less extreme position, however, would assume that stimuli are processed configurally but that generalization between them may take place which might be based on their component similarity (Pearce, 1987, 1994).

In this review, we will not only consider research conducted in the field of human causal learning but also from Pavlovian conditioning studies with human participants as well as with animals. Together with many other researchers, it is our conviction that the underlying mechanisms that govern associative learning in animals are the same as those that come into play in many situations in which humans try to make sense of the causal texture of their environment (e.g., Allan, 1993; Alloy and Tabachnik, 1984; Dickinson, 1980; Gluck and Bower, 1988; Miller and Matute, 1996; Wasserman, 1993). Although these domains might not seem too similar at first sight, one should keep in mind that animals in a conditioning laboratory face the problem of finding out "what causes what", that is, to try to learn about causal relationships. To stress their impressive capabilities, Rescorla (1988) even employed an analogy between "animals showing Pavlovian conditioning and scientists identifying the cause of a phenomenon" (p. 154).

By reviewing evidence from both human and animal research, we try to show parallels across these fields, but we also draw attention to aspects that have mainly been investigated in one domain but not in the other. In so doing, we hope to encourage cross-fertilization between the two fields and also to point out possible lines for future research. Nevertheless, we also discuss some aspects that are specific to human causal learning and that have no analogue in animal research.

1. Factors that influence whether stimuli are processed elementally or configurally

We review evidence concerning several factors that influence the manner in which stimuli are processed. These factors are task demands, prior experience, experimental instructions, stimulus properties, and stimulus organization. For this review, experimental instructions and the organization of stimuli are only discussed with regard to human causal learning research whereas the other factors are discussed with regard to both human and animal research.

1.1. Task demands

Although every discrimination problem can basically be solved configurally (at least as long as one assumes generalization between configurations, see Pearce, 1987, for examples) several problems cannot be solved elementally. Negative patterning (e.g., Rescorla, 1972a,b; Whitlow and Wagner, 1972), Saavedra's (1975) biconditional discrimination, and the feature-neutral task (e.g., Alvarado and Rudy, 1995; Holland, 1991) are typical problems that can only be solved configurally. In a negative patterning task, two stimuli are always reinforced when they are presented on their own, A+ and B+, but never when they are presented together as a compound, AB−. In a biconditional design, training involves an AB+, BC−, CD+, and DA− discrimination. And finally, a feature-neutral discrimination consists of A−, AB+, C+, and CB− training. In the negative patterning task the summation principle predicts higher levels of responding to the compound than the elements whereas a lower level is appropriate given the reinforcement contingencies. In the biconditional problem, each element is reinforced and nonreinforced equally often so that the summation principle incorrectly predicts intermediate and equal levels of responding to each compound. The feature-neutral task cannot be solved elementally because cue B cannot be an excitor across the A− and AB+ trials and at the same time an inhibitor across the C+ and CB− trials. Thus, all three discrimination problems must be solved in a configural manner in which the organism learns about the contingencies of specific cue compounds. By now, there is ample evidence from causal learning studies as well as from Pavlovian conditioning experiments showing that participants are able to master the various discrimination problems that require a configural solution (Lachnit and Kimmel, 1993; Lober and Lachnit,

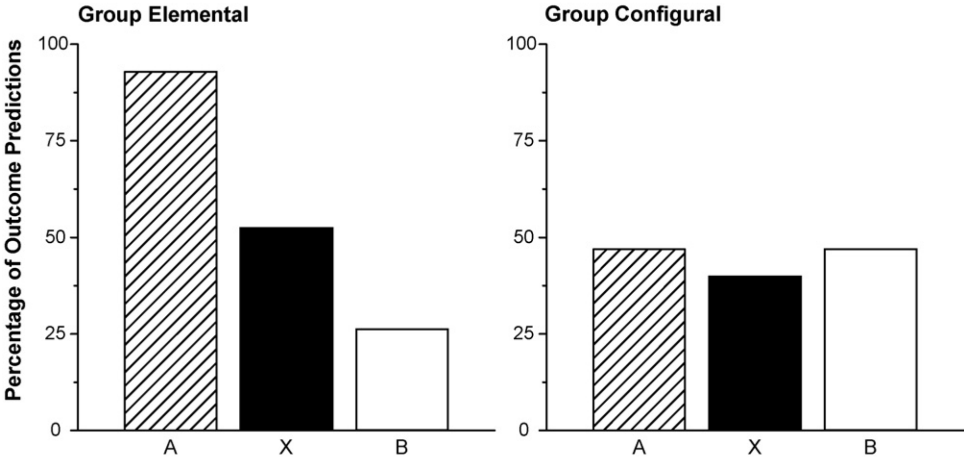

Fig. 1. Percentage of outcome predictions on test trials with A, B, and X. Prior to the test stage participants were presented with an AX+, BX- discrimination. Those in Group Elemental received an elemental pre-treatment and those in Group Configural received a configural one. Adapted from "Influence of past experience on the coding of compound stimuli," by Williams and Braker (1999), p. 466. Copyright 1999 by the American Psychological Association.

2002; Shanks, 2005; Shanks et al., 1998a; Shanks and Darby, 1998; Young et al., 2000). This evidence convincingly demonstrates that humans are able to employ a configural processing strategy when the task structure demands it.

In contrast to situations where organisms show successful acquisition of a discrimination that requires a configural solution, it is more difficult to decide whether a task that allows for an elemental solution is indeed solved elementally. If one considers, for example, an AX+, BX− discrimination, then this discrimination can be solved in either way. If this task is solved elementally, then A will be treated as a good predictor of the occurrence of the reinforcer and B as a good predictor of its absence. Furthermore, X will be treated as unrelated to the reinforcer. If, on the other hand, the task is solved configurally, in the most extreme case AX and BX may be represented as two completely distinct configurations, say Y and Z, for which no information about their components is coded. Yet, what would be observed in both cases is that responding to AX increases and responding to BX decreases during training until an asymptote is reached for each compound. In contrast to tasks that *require* a configural solution, it is therefore not straightforward to infer the manner of processing from training performance on such ambiguous discrimination problems.

Any conclusions about the way in which an AX+, BX− problem is solved therefore depend on an additional test stage, in which the different components A, B, and X are presented on their own so that responding to each can be assessed in isolation. Organisms that have solved the problem elementally should show much stronger responses to A than to B whereas organisms that have solved it in a strong configural manner should show similar levels of responding to A and B. In the latter case, this follows from the fact that their knowledge about the distinct configurations Y and Z would not be of any help when they are presented with the individual components.

An example from a causal learning study in which such different patterns of responding were observed after AX+, BX− training is shown in Fig. 1. In this experiment (Williams and Braker, 1999, Experiment 2B), the causal learning task was couched in a scenario that asked participants to determine the relationship between the illumination of different lamps and the correct functioning of a machine. Thus, A, B, and X were different lamps and the outcome was the functioning of the machine. Fig. 1 shows participants' predictions during the final test stage after they had mastered the AX+, BX− discrimination. During this test stage, participants had to predict the outcome for trials on which A, B, or X were presented on their own, without any feedback concerning the correctness of their predictions. It can be seen that participants in Group Elemental showed a pattern of responding that was in line with an elemental solution with more outcome predictions to A than to B. Predictions to X were at guessing level. In contrast to this, Group Configural showed a pattern that suggests that participants were guessing for A and B as well. This pattern is in line with a strong configural solution with no differences between responses to the three cues.

The difference between the two groups that caused this difference in response patterns relates to how they were pre-treated. During a pre-treatment stage, participants were trained with an additional problem that encouraged them to process stimuli either elementally (C+, D+, E−, CD+, and DE−) or configurally (C+, D+, E−, CD−, and DE+). The former can be solved elementally (by giving positive associative strength to C and D and inhibitory strength to E) whereas the latter requires a configural solution (since C and D are positive but the compound CD is nonreinforced). Note that both pre-treatments involve reinforcement of two elements and one compound and nonreinforcement of one element and one compound. After their respective pre-treatments, all participants received the AX+, BX− trials. In the test stage, participants responded differently to the various elements and their pattern of responding corresponded to the manner of processing encouraged during the pre-treatment (cf. Fig. 1). After elemental pre-treatment, A was assigned a higher predictive relationship with regard to reinforcement than B (Group Elemental), whereas no differences were found after configural pre-treatment (Group Configural). We have recently replicated this effect in a Pavlovian conditioning study with human participants (Melchers et al., 2004a).

Although we have said that Group Elemental's pattern of responding in Williams and Braker's (1999) experiment (and in many more experiments with both humans and animals, e.g., van Hamme and Wasserman, 1994; Wagner et al., 1968; Wasserman, 1974) was in line with an elemental solution, it should be mentioned that it cannot be distinguished from the pattern predicted by Pearce's (1987, 1994) configural theory. This theory allows for generalization between similar configurations. As mentioned above, it assumes that although stimuli are processed configurally, generalization between them will take place based on their component similarity. Thus, elemental information is used, according to this theory, to determine how similar two configurations are. As a consequence, it can also account for many elemental-like effects such as those from Group Elemental in Fig. 1. For this group, it predicts that responding to A is more pronounced than to B because excitatory strength from the compound AX generalizes to A whereas inhibitory strength from the compound BX generalizes to B due to their similarity with those compounds (see Pearce, 1987, for other examples). With regard to the data shown in Fig. 1, it cannot therefore be claimed categorically that Group Elemental did indeed solve the task elementally. In comparison to Group Configural, however, it is obvious that Group Elemental gave considerably more weight to elemental information (see next section for the reason for this effect).

The main point is that the demands of the task itself (i.e., whether it requires a configural solution or not) are likely to influence the elemental/configural balance. Two discriminations may differ marginally, yet one evokes an elemental processing mode and the other a configural one. This is seen fairly emphatically in a Pavlovian conditioning study by Melchers et al. (2004a, Experiment 2) in which participants saw either a feature-neutral discrimination (A−, AB+, C+, and CB−), which can only be solved configurally, or a matched control discrimination (A+, AB+, C−, and CB−) which can be solved elementally. Despite their similarity, these discriminations were solved differently as inferred from the fact that they had different effects on a later discrimination involving a novel set of stimuli. Specifically, when transferred to a subsequent EX+, FX− discrimination, larger responding to E than to F was evident in the group pre-trained elementally but not in the one pre-trained configurally.

1.2. Prior experience

As we have just seen, recent evidence suggests that an organism will be encouraged to process stimuli in a discrimination problem in the same way that it has processed the stimuli in another problem prior to the discrimination. In the first demonstration of this, Alvarado and Rudy (1992) trained rats in an instrumental learning study with a discrimination problem that was solved configurally. After this initial training, the animals were found to transfer their configural processing mode to another discrimination problem that would normally be solved on the basis of elemental information. In the domain of human causal learning, Williams and his colleagues (Mehta and Williams, 2002; Williams and Braker, 1999; Williams et al., 1994) have found evidence of similar effects. More specifically, participants only showed cue selection effects (which are usually explained elementally) after they had had prior experience with another problem that encouraged an elemental solution. In contrast to this, participants did not show any sign at all of elemental processing when they had worked on a configural problem before.

In the human studies cited above the conclusion that participants processed a later discrimination problem configurally after corresponding pre-training was inferred from the absence of an effect (i.e., no A/B difference) at test. In contrast to this, evidence for elemental processing was based on a positive difference (i.e., between A and B). This opens up the alternative possibility that prior training with a discrimination problem aimed to encourage configural processing had its effect on later learning not via shifting the organism towards a configural strategy but instead by simply interfering with subsequent learning. Thus, later learning of *any* discrimination task might have been impaired, and not only of tasks that might otherwise be solved on the basis of elemental information.

To rule out this possibility and to test whether configural pretraining did indeed lead to configural processing, we conducted another Pavlovian conditioning study with human participants (Melchers et al., 2005a). In this study, we used discrimination problems for the main acquisition stage for which elemental pretreatment should have an interfering effect whereas successful learning was expected after configural pre-treatment. The outcome of one of our experiments can be seen in Fig. 2. In this experiment, negative patterning (A+, B+, and AB−) was used as the target discrimination task that had to be learned during the main acquisition stage. Fig. 2 shows the overall mean level of conditioned responding during the acquisition stage to each of the different stimuli. It can clearly be seen that participants who had prior experience with a configural discrimination (Group Configural) showed good learning of the negative patterning task and showed more pronounced discrimination between the elements (A and B) that were reinforced and the compound (AB) that was not. In contrast to this, differentiation was considerably impaired after prior training with a task that should encourage an elemental solution (Group Elemental). This outcome is at variance with the possibility that configural pre-training has a nonspecific, general interfering effect on later learning because in that case Group Configural should also have had difficulties learning the negative patterning task.

Additional evidence from this study suggests a possible moderator for the impact of prior experience on later learning. In Experiment 2 of Melchers et al. (2005a), and in additional unpublished data, we found that pre-treatment had less influence when the later configural task was easier. That is, when we used a configural task that was easier to solve than negative patterning, or when measures were taken to facilitate the acquisition of negative patterning, the detrimental influence of prior training that encouraged an elemental solution was weaker.

Finally, a causal learning study by Mehta and Williams (2002) revealed another moderator, namely how well the discrimination from the pre-treatment stage was learned. They found that past experience only influenced responding in a later stage when participants' terminal level of performance on the pre-treatment

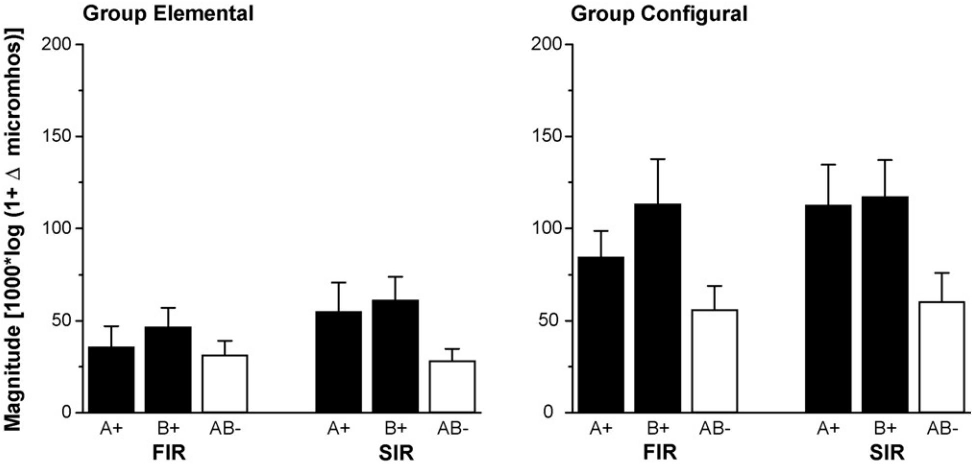

Fig. 2. Results of Melchers et al. (2005a)'s Experiment 1. Mean magnitudes of skin conductance responses during negative patterning (A+, B+, and AB−) training for participants who either received pre-training aimed at encouraging elemental (Group Elemental) or configural processing (Group Configural). FIR (first interval response) and SIR (second interval response) are different components of the anticipatory skin conductance response.

problem was good but not when it was poor. In the main learning stage, participants learned a WX+, YZ− discrimination in a task in which various chemicals (the cues) influenced the survival of a bacterium (the outcome). A subsequent test of the elements W, X, Y, and Z provided information about the extent to which the compounds were represented elementally or configurally. That is to say, a larger difference in responding to W/X versus Y/Z was taken as evidence of a greater reliance on elemental coding.

Consistent with other studies, Mehta and Williams found that prior training on an elemental problem (A+, B+, and AB+) led to stronger elemental coding in the main learning stage than prior training on a configural problem (negative patterning, A+, B+, AB−). More interestingly, they studied additional conditions in which the outcomes on the various trial types were probabilistic (the programmed outcome occurred on 80% of trials of that type) rather than deterministic (the programmed outcome occurred on 100% of trials of that type). The key finding was that the terminal level of performance of the pre-treatment moderated the extent to which that pre-treatment influenced the elemental/configural balance in the target discrimination. Although elemental and configural pre-treatments with imperfect predictors did differentially influence learning of the target problem, this effect tended to be weaker than when the pre-treatments involved perfect predictors. But the effect was due to the level of performance, and not whether the pre-treatment used perfect or imperfect predictors. Mehta and Williams (2002) concluded that the associative structures formed in a learning problem can support different degrees of generalization between a compound and its elements depending on learning strategy, and that this strategy is—as might be expected—shifted more strongly by better-learned prior treatments.

1.3. Experimental instructions

Another factor that influences processing mode in the domain of human associative learning is the use of specific instructions that encourage either a configural or an elemental strategy. In one of their causal learning experiments, Williams et al. (1994, Experiment 5) explicitly investigated this factor. They found stronger elemental processing when instructions were given that encouraged participants to view individual cues as separate entities. First, these instructions stressed that the different cues fell into one of two mutually exclusive categories, ones that are causal and always trigger the occurrence of the outcome and ones that are noncausal. Second, Williams et al. also told their participants that the occurrence of the outcome—after several cues were presented together—indicated that at least one of the cues must have been causally effective. Elemental cue selection was stronger for participants who had received these additional instructions than for a control group who had not (hence implying that the default strategy was more configural).

With regard to the potential role of instructions, it is interesting to note that some recent human Pavlovian conditioning experiments that employed instructions encouraging elemental processing were successful in obtaining prototypical elemental results like blocking (Lipp et al., 2001; Mitchell and Lovibond, 2002; Neumann et al., 1997). In a blocking procedure, cue A is initially paired with an outcome or reinforcer (A+), and then the compound of A and B is also paired with the same outcome (AB+). Blocking refers to the fact that on a subsequent test, cue B is commonly found to have little associative strength in comparison to a control group which excluded the initial A+ trials. Such a result implies elemental processing in that the AB compound must be perceived as including the familiar A element. If A and AB were perceived as entirely distinct entities, then the A+ training would not be expected to affect learning about AB+. These blocking effects in human conditioning experiments stand in contrast to various earlier experiments that were not at all or were only marginally successful in obtaining blocking (e.g., Davey and Singh, 1988; Grings et al., 1974; Kimmel and Bevill, 1996; Lovibond et al., 1988; Pellón and Garcia Montaño, 1990; Wilkinson et al., 1989). Although cross-experimental comparisons must be drawn with caution, the emerging impression is that a major difference between the successful and the unsuccessful demonstrations of elemental processing was the use of instructions that encouraged participants to view individual cues as separate entities. All of the successful reports employed such instructions whereas none of the unsuccessful ones did. Although this conclusion relates to Pavlovian conditioning experiments, the study by Williams et al. (1994, Experiment 5) described above suggests that the same factor may modulate cue competition effects like blocking in causal learning experiments too.

Although not directly related to the elemental versus configural debate, other research on human causal learning has revealed that the kind of test questions asked (e.g., Matute et al., 1996, 2002), or the time when these questions are asked (Matute et al., 2002), can have considerable impact on the outcome of a study. It might thus be possible that additional instructional aspects in a causal learning task similarly influence whether participants tend to process stimuli configurally or elementally. One possible aspect, for example, is the specific cover-story used in a causal learning study. Probably the most commonly used scenario, the food-allergy task, asks participants to find out which of several kinds of food causes allergic reactions in hypothetical patients. In our studies that employed this task, participants seemed to have no difficulties in viewing the different kinds of food as separate entities that all can have their own specific impact on the occurrence of an allergic reaction when they were given the instructions before the acquisition training (e.g., Melchers et al., 2004b). In contrast to this, Melchers et al. (2005b) reported a study which compared a food-allergy task with a so-called stock market task. The latter task asks participants to find out which of several stocks that are traded on the stock market cause changes in the overall value of the stock market. The results of the study suggested that some participants in the stock market task seemed to have the preconception that only specific patterns of trading activity will have impact on the overall value. Thus, participants seemed to be more willing to view the stock market task as requiring a configural solution than the food-allergy task (Melchers et al., 2005b). In line with this possibility, studies that used the stock market task (Chapman and Robbins, 1990; Dibbets et al., 2000; Williams et al., 1994) found weaker elemental-like effects than studies that used the food-allergy task.

1.4. *Stimulus properties*

Several researchers have claimed that the kind of stimuli used may strongly influence whether a configural or elemental processing orientation is adopted (e.g., Kehoe et al., 1994; Lachnit, 1988; Myers et al., 2001; Rescorla and Coldwell, 1995).

There is considerable evidence that even stimuli from the same modality can be processed very differently depending on whether they vary on separable or on integral dimensions. Separable dimensions combine to form stimuli with perceptually distinct components whereas integral dimensions combine to form phenomenologically fused or holistic stimuli (see Garner, 1970, 1974, for a more detailed discussion of these aspects). The prototypical examples for integral dimensions are the dimensions of colour, that is, hue, saturation, and brightness. In contrast to separable dimensions, integral dimensions are usually processed as unitary holes (i.e., configurally). Although most of the evidence for the distinction between separable and integral dimensions comes from psychophysiological experiments (see Kemler Nelson, 1993, for an overview), Lachnit (1988) has demonstrated the importance of this distinction in a Pavlovian conditioning study with human participants. He found that training with separable stimulus compounds (size of a circle and angle of a radial line) led to elemental summation when a new test compound was presented that consisted of familiar components. In contrast to this, responding to a new test compound made up of previously trained instances from integral dimensions (saturation and brightness of a Munsell chip with a constant hue) was governed by the overall similarity to specific training compounds and was indicative of a strong degree of configural processing (even stronger than would be expected on the basis of the Pearce model).

In the domain of animal learning, perhaps the most obvious aspect in this context is the use of unisensory versus multisensory stimuli. Experiments often differ with regard to whether they use compounds consisting of elements that are all from the same modality (e.g., two different visual stimuli) or that are from different modalities (e.g., a tone and a light). Although the relationship to the separable/integral dimension is rarely explored, it is of course more likely that multisensory than unisensory stimuli will vary along separable dimensions. In two experiments, Myers et al. (2001), for example, used stimuli from different modalities and found considerable evidence in favour of elemental processing while Pearce and his colleagues (Pearce et al., 1997; Redhead and Pearce, 1995) used very similar designs but employed only visual stimuli and found support for configural processing. This cross-experimental comparison is further supported by evidence from several studies that more directly assessed the impact of using stimuli from the same or from different modalities and explicitly manipulated this factor experimentally. In these studies, for example, two stimuli were first shown and reinforced on their own and were then presented together as a compound. Stronger summation of their individual associative strengths (i.e., more elemental processing) was found when the stimuli were from different modalities than when they were from the same modality (Kehoe et al., 1994; Miller, 1971). Thus, responding to multisensory compounds was more in line with an elemental mode whereas responding to unisensory compounds was more in line with a configural mode. If the compound is different from the sum of its parts then the failure to observe elemental summation is exactly what would be expected on the basis of configural processing.

Several explanations for these and related findings have been offered. The first possibility is that elements in a compound are perceived differently than when they are presented alone (e.g., Honey and Hall, 1989; Myers et al., 2001; Rescorla and Coldwell, 1995). A potential reason for this is that perceptual interactions could change the appearance of a stimulus when it is accompanied by other stimuli and that these interactions are stronger when the stimuli are from the same modality than when they are from different modalities. In the case of unisensory compounds, such interactions can already take place at the receptor-level whereas this would hardly be possible for multisensory compounds. In line with this suggestion, Honey and

Hall (1989) found evidence that pre-exposure of a cue in compound with another cue differentially affected attenuation of latent inhibition to the first cue depending on whether the second cue was from the same modality or not. More specifically, they found that when the first cue was later shown on its own and reinforced, it elicited stronger conditioned responding when it was pre-exposed as part of a compound comprised of components from the same modality compared to a condition in which it was presented together with another cue from a different modality. The animals in the latter condition, however, were similarly retarded in developing a conditioned response as animals in a standard latent inhibition condition in which the stimulus was pre-exposed on its own. Honey and Hall interpreted this finding as indicating that a stimulus is perceived as being somewhat different in the presence of another cue from the same modality compared to when it is presented alone. As a consequence of this different perception, latent inhibition will only incompletely generalize to this stimulus when it is later presented on its own. Simultaneously presenting a cue from a different modality, however, will not change the perception of the cue in question so that it will be subject to normal latent inhibition.

A second, related explanation is that masking impairs the perception of the components in a compound. Thus, they are not perceived differently in a qualitative sense, but are perceived less veridically than when they are presented on their own. Again, such a masking effect should be stronger for unisensory compounds, whose components compete for the same perceptual resources, than for multisensory compounds. Accordingly, it has been argued (Myers et al., 2001) that perceptual masking might be responsible for several of the findings that suggest stronger configural processing (e.g., Pearce and Redhead, 1993; Redhead and Pearce, 1995). On the other hand, however, one should expect that even components from the same sensory modality should be processed in a more elemental manner, as long as they do not suffer from masking effects—a prediction that has been confirmed in an experiment by Bahçekapili (1997). In this experiment, Bahçekapili trained rabbits either with an A+, AB− discrimination or with an AC+, ABC− discrimination in which an additional common element C was presented on both types of trials. According to Pearce's (1987, 1994) configural theory, the second problem should be more difficult than the first one, because the two stimulus compounds are more similar due to the additional common element. In contrast to this, theories that give more weight to elemental information predict just the opposite, so that the additional element should make the acquisition of the second problem easier compared to the first problem (see Pearce, 1994, for simulations). To assess the impact of perceptual masking, Bahçekapili only used auditory stimuli and manipulated the masking properties of the additional element C. In one group, he used a broad-spectrum noise that should considerably mask the other stimuli whereas in another group he used a clicker that should not or only weakly mask A and B. In line with predictions from the Pearce model, addition of a common noise element made the discrimination more difficult in comparison to the control group that received A+, AB− training. This replicates a similar finding by Pearce and Redhead (1993). The outcome in the group in which the clicker was used as the additional common element, however, was in line with predictions from elemental theories. In this group, animals showed better discrimination when the problem included element C in comparison to the A+, AB− group. Taken together, these results are in line with the claim that more configural processing takes place when masking impairs the perception of components in a compound than when it does not.

The results from a recent eyelid conditioning study by Kinder and Lachnit (2003), however, limit the scope of the two accounts outlined above with regard to human associative learning. In this study, conditioned responding did not seem to be influenced by perceptual interactions or by masking. In several experiments, participants were trained with an A+/B+/C+, AB+/AC+/BC+, ABC− discrimination in which each presentation of a single stimulus or of a compound consisting of two components was reinforced while the presentation of a compound consisting of all three stimuli together was nonreinforced. In their first experiment, Kinder and Lachnit used stimuli (three clearly discriminable lines on a computer screen) that should not be subject to strong perceptual interactions or to masking effects. In their second and third experiments, they used a large number of red, yellow, and green rectangles as stimuli A, B, and C, respectively, that were distributed randomly on the computer screen. These stimuli were comparable to those from an autoshaping study with pigeons by Redhead and Pearce (1995) for which it has been argued that considerable perceptual interactions and/or masking take place (Myers et al., 2001). In contrast to the results of Redhead and Pearce (see also Pearce and George, 2002), participants showed a comparable degree of differentiation between both types of reinforced stimuli and the nonreinforced ABC compound in all three experiments. This could either mean that the degree of perceptual interactions or of masking effects is not as strong as previously claimed or that humans have better discriminative capabilities for the stimuli employed and are not as strongly influenced by these factors as are some other species.

As a third explanation, some authors have suggested that modality effects could arise from the fact that stimuli from the same sensory modality share some common elements whereas stimuli from different modalities do not (e.g., Kehoe et al., 1994; McLaren and Mackintosh, 2002; Nakajima and Urushihara, 1999; Pearce et al., 2002; Wagner, 2003). That means that if a compound consists of two components from the same modality, A and B, these would not only activate their distinctive representations, say a and b, but also a common element, say x, that represents properties that A and B have in common because of their shared modality. Consequently, A and B should be conceptualised as ax and bx. With this notion, it becomes evident that they are more similar to each other than to another stimulus C from a different modality, because C would activate its distinctive representation c and perhaps an additional element y that represents properties that C has in common with other stimuli from its modality. This could explain, for example, why summation effects are more pronounced when the stimuli employed are from different sensory modalities than when they are not (Kehoe et al., 1994; Miller, 1971). In the latter case, presenting A and B in compound would activate a, b and x. As the common element x is not represented twice, this yields less summation than in the former case, where a, c, x and y are all activated.

Although some studies have found support for the claim that stimuli from the same modality have shared properties that increase their similarity (e.g., Pearce et al., 2002), this suggestion has also not remained unchallenged. Nakajima and Urushihara (1999), for example, have found that including this assumption in the Pearce model to explain results from a series of experiments makes it impossible for the model to account for the outcomes from an earlier study that used an identical design and procedure but employed stimuli from only one modality (Nakajima, 1997).

To complicate matters even more, some experimental outcomes are contrary to the general pattern of results that emerges with regard to the use of unisensory versus multisensory compounds. Rescorla (1972b), for example, has found that presenting an additional element C on each trial of a negative patterning problem (AC+, BC+, and ABC−) makes acquisition of the discrimination more difficult compared to a group that only received A+, B+, and AB− training. He obtained this finding, which is difficult to reconcile with elemental processing, even though C was from a different sensory modality than A and B and so should not perceptually interact with them, mask them, or have common elements with them. Similar effects have usually only been obtained in experiments that employed stimuli that were all from the same modality (Pearce and George, 2002; Pearce and Redhead, 1993; Redhead and Pearce, 1995). On the other hand, Deisig et al. (2003), in a comparable study, have found evidence that is more in line with a position that gives more weight to elemental information, although they used stimuli from only one sensory modality.

Perhaps some of the confusing results could be sorted out if more was known about the psychophysical properties of the stimuli employed in the different experiments.

1.5. Stimulus organization

In the last section, we discussed the possible influence of perceptual interactions between the components of a compound. It seems especially plausible to assume that such interactions might take place between localized visual cues that are presented very close to each other as is usually the case in autoshaping experiments with pigeons. Stimulus organization, however, might also play a role in the domain of human causal learning where perceptual interactions are much less likely to take place because of the use of clearly discriminable stimuli.

Glautier (2002; see also Martin and Levey, 1991) conducted blocking experiments in which the cues were spatially close together and grouped or spatially separated and ungrouped. The cues were symbols presented on cards. When the pretrained and target cues appeared on the same card (i.e., both spatially proximal and grouped) little evidence of blocking was found, consistent with configural processing. However, when the cues appeared on different cards (i.e., both spatially distal and ungrouped), blocking was observed, consistent with elemental processing. An experiment which attempted to unconfound grouping and spatial separation suggested that the latter was the dominant feature. Similar results were reported by Livesey and Boakes (2004).

In most causal learning studies, only the relevant cues are presented on a given trial. In other words, on an A+ trial, only cue A and the reinforcer are shown to the participants whereas no information about other cues (for example B and C) are given that might also be used in the experiment but that are not relevant on this particular A+ trial. This is the procedure most often used (e.g., Aitken et al., 2000; Matute et al., 1996; Melchers et al., 2004b; Shanks, 1985; Wasserman and Berglan, 1998; Young et al., 2000). In some studies, however, a list of all the cues used in the experiment was presented on each trial (Chapman and Robbins, 1990; Williams and Braker, 1999; Williams et al., 1994). Thus, on each trial additional information was given for each cue indicating whether it was present or relevant on the trial or not. The participants' task in those experiments was, for example, to predict the change in the market index of a fictitious stock market and the cues were the names of several different stocks. These names were presented in a list and a second list of *yes*'*s* and *no*'*s* next to the first list indicated whether a stock was traded or not.

Melchers et al. (2005b) have investigated this topic in an experiment that directly compared the two different stimulus arrangements (only the relevant cues versus list-wise presentation of all cues). The tasks were a stock market one in which the cues were particular stocks that were or were not traded on a given day and the outcome was a rise in the overall market value, and a food allergy task in which the cues were foods eaten by a hypothetical patient and the outcome was the development of an allergic reaction. Melchers et al. speculated that experiments that used a list-wise presentation of cues have often found weaker effects of elemental processing than studies in which only the relevant cues were presented on a trial. It is possible that presentation of only the relevant cues stresses the elemental nature of the stimuli whereas participants treat the positional cues in a list-wise presentation format more configurally. Perhaps they even try to learn specific yes-no patterns instead of only paying attention to the "relevant" cues—which might be a plausible strategy for them given the fact that they do not actually know which pieces of information are relevant from the experimenter's point of view and which are not. However, the results were not consistent with this prediction: presentation format made no difference to participants' causal ratings (in contrast, the nature of the task did make a difference—cue competition was much stronger in an allergy than a stock market task).

Other evidence seems (rather counterintuitively) to contradict the hypothesis. Dibbets et al. (2000) again used a stock market task and manipulated whether the different cues were always presented in the same position of a list-wise stimulus arrangement or not. It turned out that participants showed evidence for elemental cue competition only if the position of the cues remained constant from trial to trial—a format that might be expected to encourage configural processing. If the position of the cues varied, no such cue competition was obtained. This indicates that participants in the latter condition could not make use of information that was potentially embedded in the arrangement of the stimuli, that is, in non-spatial information about the presence/relevance of the different cues. This is plainly an area where more research is needed.

1.6. Concluding comments on factors that influence elemental versus configural processing

Taken together, the evidence reviewed in this section suggests that whether stimuli are processed more elementally or more configurally is not fixed but can instead be influenced considerably. As we have tried to show above, this claim is supported by evidence from human as well as from animal learning experiments and regardless of whether causal learning or Pavlovian conditioning paradigms were employed. Thus, a multitude of findings from different species, different paradigms, and different laboratories has shown that it is incorrect to assume that stimuli are always processed in one and the same way. Instead, human learners as well as other organisms seem to be rather flexible with regard to whether they process stimuli elementally or configurally when they try to make sense of the causal relationships in the world. Thus, they are able to adjust the way stimuli are processed depending on various demands such as the nature of a learning task, the stimuli they are confronted with, their prior experience, the instructions (in the case of human learners) that they receive before they start to work on a problem, or the arrangement of the different stimuli. Notably, this flexibility is at variance with several well-established theories of associative learning (e.g., Mackintosh, 1975; Pearce, 1987, 1994; Pearce and Hall, 1980; Rescorla and Wagner, 1972; Wagner, 1981). Although these theories disagree with regard to whether they assume that stimuli are processed elementally or configurally, they all agree that the processing strategy cannot be flexible but instead always remains fixed. Thereby, they underestimate the power with which nature has equipped learning organisms to adjust to diverse and probably often even changing environmental demands.

Another factor which can have a profound effect on processing mode is the integrity of the hippocampal formation. It is well-known that hippocampal lesions can affect animals' and humans' ability to solve configural discriminations whilst leaving elemental learning largely intact. We do not review the extensive and somewhat complex literature on this topic (see Moses and Ryan, 2006; O'Reilly and Rudy, 2001, for reviews), but we note that the ability to shift learning mode on the elemental/configural dimension via brain interventions supports our general claim that processing mode is not fixed. Research has also begun to use single-cell recording techniques to investigate the role of other brain systems (e.g., inferotemporal cortex) in representing parts and wholes (Baker et al., 2002).

2. Theoretical implications

The results from the experiments reviewed above show that the either/or manner in which the question of elemental versus configural processing is usually discussed is based on an incorrect underlying assumption. This assumption, which is common to both approaches, is that the manner of processing is always the same. The crucial question, however, is not whether stimuli are always processed in one way or the other, but instead which factors influence the manner of processing. As a consequence, theoretical models that allow for the necessary flexibility are needed. In the following paragraphs, we will present an overview of the different models that have been offered and that permit greater flexibility. The main distinction between these models is whether they suggest an elemental-configural continuum on which stimulus processing may vary (Wagner and Brandon, 2001; Williams and Braker, 1999; Williams et al., 1994) or whether they assume that organisms have two different learning systems, an elemental one and a configural one (Fanselow, 1999; Rudy and Sutherland, 1995; Schmajuk and DiCarlo, 1992). We will first discuss three models that follow the former approach. Two of them have originated from the elemental tradition. They assume that stimuli are represented elementally and that configural information is either coded in addition to these elemental representations or replaces some of them. In contrast to this, the third model introduces a modification of the configural point of view. After these models, we will describe views that propose two distinct learning systems whose interaction might be highly nonlinear.

2.1. Unique cue extensions of elemental theories

One of the simplest ways in which associative theories can allow for both elemental and configural processing would be to assume that stimulus components are always encoded elementally, but that configurations of those components may additionally be encoded by specific configural units which are treated as if they are additional "elements" and whose activation sums linearly with that of the elemental units. According to such a view, the overall associative strength of a compound (e.g., AB) is based on the summed associative strength of its elements plus the associative strength of the additional "configural element", as formally shown in Eq. (2):

$$V_{AB} = V_A + V_B + V_{\text{unique}} \qquad (2)$$

where V_A and V_B are the associative strengths of the elements A and B and V_{unique} is the associative strength of the configural unit that codes the unique combination of A and B. By postulating the existence of such configural units (usually called *unique cues*), elemental models of associative learning can successfully handle the acquisition of discrimination problems like negative patterning, biconditional, or feature-neutral discrimination that are at variance with purely elemental models but which instead require a configural solution. Negative patterning (A+, B+, and AB−), for example, can be explained by assuming that A and B will both develop excitatory associations to the reinforcer and that their unique cue will develop an inhibitory association with this reinforcer. When A or B are presented on their own, each will be able to activate a representation of the reinforcer so that a conditioned response will be elicited. On trials on which A and B are presented together, however, their joint presence will activate the unique cue which can then compensate for their excitatory properties due to its inhibitory associative status.

The unique cue view has long been known as an extension of elemental models that allows for quite a large degree of configural processing while at the same time keeping the spirit of those models, that is, the elemental summation principle that is shown in Eq. (1) (Rescorla, 1972b, 1973; Whitlow and Wagner, 1972). And although the unique cue idea has usually been discussed as an extension of the Rescorla and Wagner (1972) model of associative learning, it should be noted that it can basically be used as an extension of other elemental models as well.

With regard to the influence of integral versus separable stimulus dimensions or elemental instructions on elemental versus configural learning, one could assume that these modulate the salience of the different cues. Instructions that stress the individual or additive nature of the stimuli in question could thereby help to increase the salience of the different elements concerned to the disadvantage of the respective unique cues. Similarly, the use of integral stimuli would increase the salience of unique cues while at the same time making individual elements less salient.

With regard to the influence of past experience, it would be necessary to assume that all unique cues are less salient after elemental pre-training and more salient after configural pre-training (Williams and Braker, 1999). The important aspect to note about this suggestion is that the impact of past experience should not be limited to configural units of compounds that are actually presented during pre-training. Instead, past experience should also increase the salience of unique cues that are activated by other compounds.

As an alternative to this salience modulation, it could be assumed that the unique cues always have the same salience but are more or less able to inhibit the representations of their corresponding individual components (Kehoe, 1988). If the degree of inhibition from all the unique cues is generally enhanced after configural pre-training, organisms should show stronger configural processing. Similarly, if less inhibition takes place after elemental pre-training, then stronger elemental processing is expected. The use of integral versus separable compounds or experimental instructions could have the same kind of moderating effect on the unique cues.

A serious limitation of unique cue extensions of elemental theories, however, is that they can only explain certain results if they assume that just the unique cue is active on compound trials and that the individual components of the compound are then of no importance at all. It has, for example, been shown that animals in a conditioning study (Pearce and Wilson, 1991) as well as humans in causal learning experiments (Shanks et al., 1998a,b) can preserve an A+, AB− discrimination even in the face of later B+ training which should abolish this discrimination. According to an elemental solution, B should have inhibitory associative strength at the end of the A+, AB− training. B+ training should then turn B into an excitator, so that responding to AB in a subsequent test phase should be stronger than to A. In contrast to this prediction but in line with the original A+, AB− discrimination, responding to AB in the test was weaker than to A alone. As mentioned above, this outcome can only be explained by unique cue models if they assume that just the unique cue is active during AB presentations (or at least that it is so dominant that the elements can practically be ignored). In that case, B+ training should not affect the original discrimination. Yet, such an assumption would turn the elemental unique cue extensions into purely configural models and thereby defeat the original intentions of their proponents (e.g., Rescorla, 1973; Wagner, 1971).

2.2. *The replaced-elements model*

The recently introduced *replaced-elements model* of Wagner and Brandon (2001) and Wagner (2003) also follows the elemental tradition and is based on a similar idea to the unique cue hypothesis. It assumes that each stimulus is mentally represented by several elements that are all activated when the stimulus is presented on its own. For trials in which a stimulus is shown as part of a compound, Wagner and Brandon suggest that some of its elements are inhibited or suppressed but that additional configural elements are activated. These configural elements code the specific combination of the respective stimulus with another cue and replace the inhibited elements (see McLaren and Mackintosh, 2002, for a related idea). It has been proposed that the replaced-elements model allows for considerable flexibility with regard to the way stimulus compounds are processed if more or fewer of the specific elements of a stimulus are replaced by configural elements (Myers et al., 2001; Wagner, 2003). Myers et al., for example, have suggested that a larger number of specific elements are replaced by configural elements when an organism is faced with integral stimuli whereas relatively few specific elements are replaced when it is confronted with separable stimuli. Similarly, prior experience with elemental pre-training could encourage a general tendency to replace only relatively few specific elements by configural elements whereas prior experience with configural pre-training has the opposite effect. And finally, specific instructions could also motivate a learner to focus more on single elements or more on specific combinations of stimuli so that he or she would process a problem in a more elemental manner or in a more configural way.

In contrast to the unique cue hypothesis, the replaced-elements model does not suffer from the problems described above (Pearce and Wilson, 1991; Shanks et al., 1998a). In the extreme, all the elements of a stimulus might be replaced by configural elements, so that the replaced-elements model would indeed function like a purely configural model—a possibility that is explicitly intended (e.g., Wagner, 2003). Thereby, it could allow for the preservation of the original A+, AB− discrimination even after B+ training.

2.3. *Configural processing*

As noted above, the previous accounts have in common that they assume that stimuli are represented elementally and that configural information is coded in addition to elemental representations. The degree to which responding is indicative of either elemental or configural processing would always depend on the impact that the additional configural or unique cues have relative to the elemental cues. In contrast to this, it could also be assumed that stimuli are always represented configurally. As noted in the introduction, the strongest view on how such configural representations might be formed is that a compound is represented in a way that is distinct from its elements and that responding to it is not influenced at all by what is learned about the elements and vice versa. Such a view would be a purely configural one and it has long been known to be at variance with experimental evidence from the domain of animal conditioning which shows mutual influences between elements and compounds (for a review see Kehoe and Gormezano, 1980). Some of the evidence from the field of causal learning, however, suggests that human participants may indeed show no generalization between a compound and its elements under some circumstances (e.g., Shanks et al., 1998b; Williams and Braker, 1999; Williams et al., 1994).

A less extreme position would assume that stimuli are processed configurally but that generalization between them takes place. According to the most prominent configural theory (Pearce, 1987, 1994, 2002), the degree of generalization between two stimuli is based on their component similarity, that is, on the number of elements they share. Thereby, part of the associative strength of a compound can generalize to its elements and vice versa.

In addition to the degree of component similarity, Williams and Braker (1999) have suggested an additional generalization parameter that allows for a flexible degree of generalization and that is independent of the number of elements shared by two compounds (see also Kinder and Lachnit, 2003). Less generalization would lead to stronger configural processing whereas more generalization would lead to more elemental-like behaviour. According to such a conception, stimuli would always be processed configurally. Factors encouraging elemental processing would not cause organisms to actually process stimuli elementally, but instead the organism would be more prepared to generalize the associative strength of one configuration to another based on their component similarity. Likewise, measures to foster configural processing should lead to weaker generalization between different configurations. In the most extreme case, hardly any generalization between different configurations might take place.

The introduction of such a generalization parameter makes Pearce's (1987, 1994) model similar to Kruschke's (1992) ALCOVE model, a configural model from the field of human category learning in which such a parameter is already included. Thus, the possible influence of the different factors on elemental versus configural processing also applies to ALCOVE. Similarly, Kehoe's (1988, 1998) layered network model—in which all learning is mediated by hidden units—could potentially explain instances of representational flexibility in this way. A discussed more fully in the next section, the beauty of network models with hidden units is that they are able to internally organize their representational resources in the way that is best suited for the particular problem at hand. Thus Kehoe's model is able to decide to make one hidden unit configural (only triggered by the conjoint input of A and B) and another one elemental (triggered by either A or B).

2.4. Two learning systems

With regard to the possibility that organisms can deploy two different processing systems, Fanselow (1999; see also Rudy and Sutherland, 1995) has put forward the view that stimuli are always processed elementally and configurally. Thus, when a stimulus compound (e.g., AB) is presented to an organism and is reinforced, its elements are represented as distinct elements in the first system and are at the same time represented as a configuration in the second system. Within each system, associations between these representations and the reinforcer will be learned. Inputs from both processing systems then compete with each other for the limited amount of associative strength that is supported by the US.

This idea is formalized in much more detail in a connectionist model developed by Schmajuk and co-workers (Schmajuk and DiCarlo, 1992; Schmajuk et al., 1998). Although others have considered the representation of elements and configurations in models with flexible internal representations too (Delamater et al., 1999; Gluck and Myers, 1997), Schmajuk's model has been more comprehensively analyzed with respect to specific behavioural phenomena. The essence of the model is that units representing the elements of which stimuli are composed connect directly with output units but also with a set of hidden, configural units. The activations of these two sets of units compete with each other for control of responding and this competition is crucial in distinguishing the model from the unique-cue approach. In the latter, the error on a given learning trial drives changes across both the elements present on that trial and the unique cue configurations created by those elements, and the only factor that affects the relative changes for the elements and unique cues are their saliences. Although we suggested above that the salience of unique cues relative to the salience of "real" elements may change depending on various factors, there is no inherent mechanism for how this weighting is achieved. In Schmajuk's model, by contrast, the backpropagation-of-error rule explicitly takes into account how diagnostic a given unit is for determining the output and bases strength changes on this. Hence if a stimulus configuration is much more predictive of the reinforcer than the elements that compose it, the model can tune out the elements and give them little associative strength, and vice versa. Weight changes depend on the influence of each hidden unit on the output error.

Although the two sets of units interact closely, Schmajuk and colleagues (Schmajuk and DiCarlo, 1992; Schmajuk et al., 1998) have proposed that they relate to distinct brain circuits and thus at this level it is clear that they constitute distinct "systems". For instance, the hippocampus is assumed to be particularly critical for hidden unit learning. The model has been successfully applied to a range of learning phenomena and shown capable of organizing itself under different conditions to place less or more emphasis on configural coding. Most of these examples relate to occasion setting and hence fall outside the scope of the present review. In occasion setting, a stimulus comes to control responding to another stimulus without itself being directly associated with the reinforcer. For instance, in a feature positive discrimination of the form A−, XA+, the feature cue X might come to control the degree of responding to stimulus A without acquiring significant associative strength for the reinforcer. Schmajuk et al. (1998) showed that quite superficial manipulations such as the relative saliences of X and A or whether X and A were simultaneous or successive could have a major impact on how the model represented the XA configuration.

Such examples offer the tantalizing prospect that the sorts of findings reviewed in the present article might be interpreted within this modelling framework. However, it remains to be explored how successful the model would be at dealing with some of the cases we have reviewed of representational flexibility. For instance, additional assumptions would need to be made to allow the model to be applied to conditions in which the spatial separation of cues varied or in which pre-treatments with different cues or experimental instructions altered the solution to a target discrimination.

2.5. Limitations

A problem inherent to all modifications outlined above as well as to other recent suggestions of new or modified models (McLaren and Mackintosh, 2002; Pearce, 2002; Wagner, 2003; Wagner and Brandon, 2001) is that they make the predictions of the different theories less clear cut than before. On the one hand, researchers in the field of associative learning are progressively abandoning the incorrect and inflexible either/or manner in which the question of whether stimuli are processed elementally or configurally has usually been couched. However, by suggesting, for example, that the salience of unique cues or the degree of generalization between different configurations might be influenced by a certain factor, one has only argued that such a modification might basically allow for the necessary degree of flexibility. The introduction of new adjustable parameters—that is, of additional degrees of freedom—also has the consequence that it becomes much harder to generate critical predictions from the theories. Thus, it becomes crucial to specify how exactly the mechanism that is responsible for the flexible adjustment of the processing strategy works. Hence it remains to be laid down, for example, how the salience of the different unique cues or how the degree of generalization between different configurations will be determined on the basis of the various factors. Only then will it be possible to make more specific predictions about which mode of processing will take place in a given situation.

3. Lines for future research

In this last section, we try to outline several possible lines for future research that we consider as necessary and promising next steps.

First, for some of the factors reviewed in the second section, the present evidence is largely based on either human or animal research. Although we have argued above that we are convinced that human causal learning and animal conditioning are based on the same underlying mechanisms, this does not render demonstrations of cross-species generality of the different factors unnecessary. Therefore, research with animals is needed to evaluate whether the finding that prior experience influences later processing of stimuli is true for the field of animal learning as well. So far, the main evidence with regard to this factor comes from the field of human associative learning. Although Alvarado and Rudy (1992) have reported evidence for the impact of prior experience on later elemental versus configural learning in rats (see also Beckers et al., 2006), a study by Williams and Braker (2002) failed to find any effect. In addition to this, future research should try to assess the relative contributions of elemental versus configural pre-training. Although it has been shown that the different kinds of pre-training lead to differential effects on later learning, it remains to be seen whether both kinds of pre-training are equally effective with regard to inducing a processing strategy. As an alternative, it could be that one kind of pre-training has a strong influence whereas the other one only slightly enhances or weakens a pre-experimental bias to process stimuli in one way.

Similarly, more research on the psychophysical properties of the stimuli used in animal experiments seems necessary. As described above, stimuli based on integral dimensions were processed configurally whereas stimuli based on separable dimensions were processed elementally in a Pavlovian conditioning study with humans (Lachnit, 1988). Unfortunately, there is only very limited knowledge of whether the stimuli used in animal conditioning experiments are based on integral or on separable dimensions. The only investigation that we are aware of concerns the question of how colours are processed by honeybees (Backhaus, 1987). In this investigation, it turned out that honeybees seem to process colours in a manner that would be usual for separable stimuli—quite different to what would be expected on the basis of evidence from the field of human colour perception.

With regard to the influence of unisensory versus multisensory compounds, human causal learning research could help to assess the validity of the claim that stimuli should only be processed configurally when perceptual interactions between the components of a compound take place or when components mask each other. Usually, the stimuli used in a causal learning experiment (e.g., different kinds of food that might cause an allergy) are presented in a way that does not make perceptual interactions or masking effects very probable. If, for example, such research reveals that the addition of a common cue has the same effect on solving certain discriminations as was found in Pearce's laboratory (Pearce and Redhead, 1993; Redhead and Pearce, 1995), this would constitute rather unambiguous evidence for configural processing.

Second, more research is needed to compare the impact of different stimuli within the same study. Although it is often claimed that the use of different stimuli constituted the main difference between two studies and might therefore be responsible for discrepant results, this argument often rests on grounds of plausibility only. Until now, only very few investigations have directly compared stimulus properties within one and the same study (e.g., Glautier, 2002; Honey and Hall, 1989; Kehoe et al., 1994; Lachnit, 1988; Miller, 1971) so that more work seems necessary that explicitly varies the nature of the stimuli used for conditioning. Strong evidence for the impact of unisensory versus multisensory compounds would involve demonstrating that those stimuli that are more likely to be processed elementally and that yield pronounced elemental summation after separate reinforced training will lead to difficulties when used for a discrimination that requires a configural solution. Similarly, the opposite effect should be found for stimuli that are more likely to be processed configurally. Thus, similar to the studies on summation effects, one could use either stimuli from the same modality or from different modalities for training with a negative patterning or a biconditional discrimination, for example. If stimuli from different modalities are in fact processed more elementally, then their use for a problem that requires a configural solution should make that problem more difficult.

Third, several factors that are specific to human causal learning experiments and that do not apply to animal learning also demand further attention. We have already pointed out the possibility that differences in the arrangement of stimuli might influence the degree to which they are processed in one manner or the other. Furthermore, it seems desirable to gather more knowledge about the impact of instructional factors with regard to elemental versus configural processing.

Lastly, at the theoretical level, more work is needed in developing and applying specific formal models to the key behavioural results. In particular, models with the flexibility to tune their own internal representations (Kehoe, 1988; Schmajuk and DiCarlo, 1992) need to be applied to some of the experimental designs involving pre-treatments and so on. The success of these models in explaining related phenomena like occasion setting (Schmajuk et al., 1998) offers good hope that they might also yield insights concerning the flexible representation of parts and wholes.

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