Incidental Learning of Simple Stimulus-Response Associations:

A Review of Colour-Word Contingency Learning Research

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Abstract

In this article, I review research on incidental learning of simple stimulus-response regularities. The article summarizes work with the colour-word contingency learning paradigm and related simple learning procedures. In the colour-word contingency learning paradigm participants are presented with a coloured neutral word on each trial and are asked to ignore the word and respond to the print colour (e.g., similar to a Stroop procedure). Distracting words are typically colour-unrelated neutral stimuli. However, each distracting word is presented most often in one target colour (e.g., “move” most often in blue, “sent” most often in green, etc.). Learning of these contingencies is indicated by faster and more accurate responses to high contingency trials (in which the word is presented with its frequent colour) relative to low contingency trials. This procedure has proven useful for investigations in incidental learning. The present manuscript summarizes the existing work with this (and related) learning procedures and highlights emerging directions.

Keywords: contingency learning, incidental learning, awareness, cue competition, conditioning

Introduction

A general principle of human statistical learning is that we are sensitive to the regularities that surround us (Brent & Cartwright, 1996). For adults (Saffran, Newport, & Aslin, 1996) and children (Saffran, Aslin, & Newport, 1996), for example, a few minutes of listening is enough to detect the boundaries between pseudo-words that follow the rules of an artificial grammar. We are well equipped to detect, not always consciously, informative regularities, usually very quickly. These regularities allow us to maximize performance, responding faster and more accurately to events that are consistent with a learned regularity versus events that are unpredictable or incompatible with a regularity (Perruchet, 2019; Perruchet & Pacton, 2006; Thiessen, Kronstein, & Hufnagle, 2013).

There are many different approaches to studying how participants learn about regularities in their environment. In addition to explicit learning and decision-making procedures where the participant has the direct objective of learning the regularities in the task, such as the allergy prediction task (Van Hamme & Wasserman, 1994) or various complex system tasks (e.g., Brehmer, 1992; Sterman, 1989, 1994), paradigms also exist to study learning of a more incidental nature. In *incidental learning procedures*, the goal of participants is to complete a simple task (e.g., colour identification), but there are other cues in the task (e.g., distracting words) that seem irrelevant to achieving the main goal. These cues are actually informative, due to a certain regularity programmed in the experiment. The influence of these irrelevant (but, indeed, informative) regularities on performance (e.g., faster responses to trials that obey the regularity compared to those that do not) indicates contingency learning that is incidental to the primary objective of the task. Such incidental learning can either indicate a kind of implicit/unconscious learning or show that participants deliberately tried to learn regularities despite the absence of instructions to do so.

There are also many approaches to studying incidental learning, many of which involve relatively complex regularities, such as the learning of predictable sequences of trials (Nissen & Bullemer, 1987; Turk-Browne, Jungé, & Scholl, 2005), of artificial grammars (Reber, 1967; for a review, see Pothos, 2007), or lists of repeated digits (Oberauer, Jones, & Lewandowsky, 2015; Mckelvie, 1987; Vachon, Marois, Lévesque-Dion, Legendre, & Saint-Aubin, 2018). A particularly interesting and simple incidental learning procedure that will be at the center of this review is the *colour-word contingency learning task* (Schmidt, Crump, Cheesman, & Besner, 2007). In this procedure, a coloured word is presented to the participant on each trial. Their task is to ignore the word itself and respond to the colour in which the word is printed. This is similar to a Stroop task (Stroop, 1935; MacLeod, 1991), except that distracting words are colour-unrelated (e.g., words like “move”, “send”, and “tell”). Crucially, each word is most often presented in a single colour (e.g., “move” most often in blue and rarely in green or red, “send” most often in green, etc.), as shown in Table I. Thus, although the words are not task relevant, they are informative about the likely target colour (and the response). These contingencies are learned as indicated by faster and more accurate responses to *high contingency* stimuli (e.g., “move” in blue) compared to low *contingency* stimuli (e.g., “move” in red). The design in Table I is fairly standard, with three distractor words and three target colours, but the effect is also present with more stimuli (e.g., nine words in the experiments of Schmidt & De Houwer, 2012c).

Table I. Typical colour-word contingency learning manipulation.

Colour	Word		
	move	send	tell
blue	**8**	1	1
red	1	**8**	1
green	1	1	**8**

This task proves to be a useful tool in the study of contingency learning. Not only are the regularities remarkably simple (i.e., stimulus pairings with a high cooccurrence frequency compared to those with a low frequency), but the learning effects are large and robust. Indeed, very few participants do not show a numerical advantage for high contingency trials over low contingency trials. To illustrate this robustness, Figure 1 shows box-and-whisker plots for response time data from some of our studies with a colour-word contingency learning manipulation like that in Table I. Although not as “visceral” as the Stroop effect, the colour-word contingency learning effect is just as faithful (e.g., the η^2s for the 5 experiments in Figure 1 are respectively .59 (n = 36), .80 (n = 34), .49 (n = 62), .52 (n = 25), and .51 (n = 46), all ps < .001).

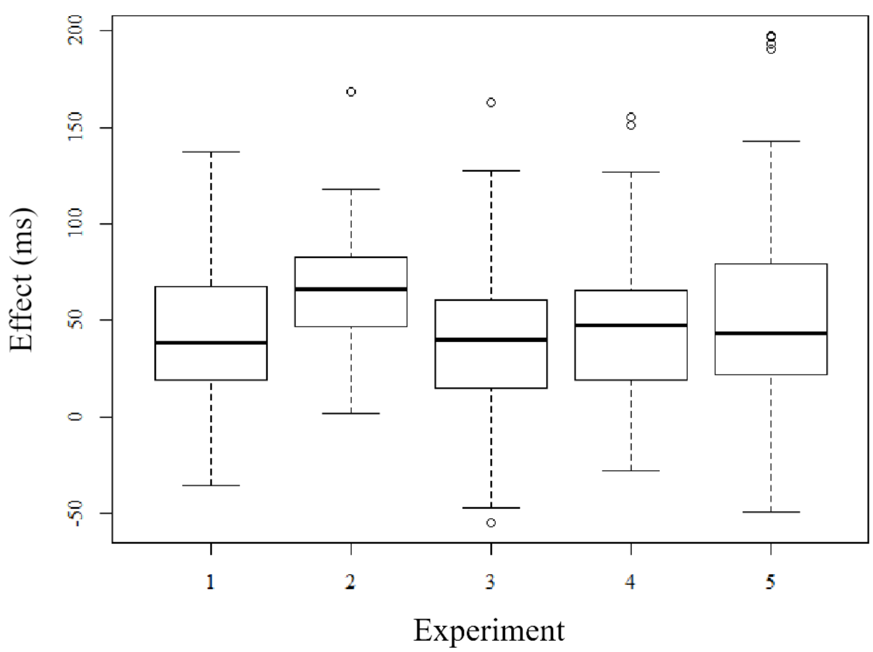

Figure 1. The contingency effect in five experiments. 1 = Experiment 1a of Schmidt et De Houwer (2016b), 2 = Experiment 1b of Schmidt et De Houwer (2016b), 3 = Experiment 1 of Schmidt et De Houwer (2012d), 4 = Experiment 3 (control condition) of Schmidt et De Houwer (2012d), 5 = Schmidt and De Houwer (2012a).

A useful feature of the colour-word contingency learning procedure is that the influence of regularities can be assessed during the learning phase itself. This is partly due to the fact that events consistent with the regularities (high contingency trials) are mixed with events incompatible with the regularities (low contingency trials). Non-predictive stimuli can also be mixed with other trial types (Lin & MacLeod, 2018; Schmidt & De Houwer, 2016a). This is different from a study-test procedure, such as that in the experiments of Musen and Squire (1993). Their studies were divided into two phases: a study phase with perfect contingencies (i.e., no low contingency trials) and a test phase where word-colour combinations were random to test the transfer of the initial contingency. But with the colour-word contingency learning paradigm, its probabilistic nature is useful because it is very easy to see how the learning effects change with more training. All trials of the experiment contribute both to the strengthening of learning and to the measurement of the learning effect. In a study-test design, we can only evaluate the test trials and learning is actually evaluated during unlearning, where regularities have been removed. There are also probabilistic versions of sequence learning. The standard sequence learning procedure is to compare perfectly predictable stimulus and response sequences to random sequences, as well as an assessment of a decrease in performance when a predictable sequence becomes random (Nissen & Bullemer, 1987). However, probabilistic sequence learning procedures involve the use of predictable sequences with occasional trials that violate the sequence (Jiménez, Méndez, & Cleeremans, 1996).

The colour-word contingency learning task is now widely used (see MacLeod, 2019), but it is similar to some related paradigms that have seen more limited use. For example, Miller (1987; see also, Carlson & Flowers, 1996; Mordkoff & Halterman, 2008) introduced the flanker contingency paradigm in which participants respond to a target letter while ignoring distracting letters that flank the target to the left and right. Similar to the colour-word contingency learning procedure, distractors (in this case, flankers) are predictive of the target (in this case, the central letter). In other studies, shapes, colours, nonwords (e.g., “alsan”), and foreign language words have been used instead of words; colour words, neutral words, and positive or negative words were used as targets, instead of colours (Atalay & Misirlisoy, 2012; Forrin & MacLeod, 2017; Levin & Tzelgov, 2016; Lin & MacLeod, 2018; Schmidt & De Houwer, 2012b, 2012c, 2019b). Somewhat more complex covariation learning procedures have been described by Lewicki and colleagues (Lewicki, 1985, 1986; Lewicki, Hill, & Czyzewska, 1992), although these procedures are only weakly reproducible (Hendrickx & De Houwer, 1997; Hendrickx, De Houwer, Baeyens, Eelen, & Van Avermaet, 1997a, 1997b; Hendrickx, Eelen, & Van Avermaet, 1997). In any case, this review will also cover some studies conducted with paradigms similar to the colour-word contingency learning task. It should be noted that there is another review of the literature with this procedure (MacLeod, 2019), which has some overlap, but limited, with the present article. The other review does not cover the same fields of research. It is shorter and also focuses on the contributions of Prof. MacLeod (the review is associated with a gold medal from the Canadian Psychological Association), but it takes into account some works (unpublished but interesting) that this article does not present. Thus, I recommend both reviews to interested readers.

The present review examines nine lines of research in separate sections below. The section “Intention, Consciousness, and Cognitive Resources” explores the role of contingency awareness in learning, contrasts intentional and incidental learning, and explores whether the encoding or retrieval of knowledge about contingencies depends on cognitive resources. The “Stimulus-Stimulus Learning vs. Stimulus-Response Learning” section explores whether learning effects are the result of learning stimulus pairings (word-colour) and/or stimulus-response regularities (word-keyboard response). The “Learning Rate and Frequency” section explores the speed of learning, unlearning, and relearning, and how response time varies with the strength of the contingency between distractors and responses. The “Categorical Learning” section describes work on learning abstract regularities. The “Evaluative Learning” section deals with an adaptation of the task that can be used to study evaluative conditioning. The “Temporal Contiguity” section explores the extent to which variations in stimulus onset asynchronies and inter-stimuli intervals between distractors and targets influence learning effects. The “Compound Cues” section explores the extent to which participants are able to learn from regularities defined by the combination of stimuli. The “Cue Competition and Incidental Learning” section discusses research on whether blocking and overshadowing effects can be observed with incidental learning. The “Learning and Binding” section explores the relationship between learning effects and the effects of recent experiences (binding effects). Finally, this review concludes with some final reflections on the implications of the work already done with the task and on the future avenues to be developed.

Intention, Consciousness, and Cognitive Resources

A frequently debated issue in the statistical learning literature is the role of awareness in learning (Cleeremans, Destrebecqz, & Boyer, 1998; Frensch & Rünger, 2003; Shanks, 2005; Shanks & St John, 1994). Interestingly, the learning effects observed in the colour-word contingency learning procedure seem to be by nature primarily implicit. In the classic procedure, participants are simply asked to respond to the colours and are not informed about the regularities between words and colours. Many participants eventually become aware of contingency biases in the procedure, but many others do not. Among the participants who are not at all aware of the contingency manipulation, the contingency effect is still large and robust (e.g., Schmidt et al., 2007). Defining what constitutes evidence of “implicit” learning is a particularly thorny issue (e.g., Cleeremans, 1997; Shanks, 2005), but the effect is clearly present in participants who are not subjectively aware (i.e., able to signal that they have noticed a contingency) and those who are not objectively aware (i.e., able to guess above chance which words are presented in which colours). Specifically, for the measurement of subjective awareness (e.g., see Schmidt et al., 2007), right after the learning phase we explained the contingency manipulation (e.g., "one word was presented most often in blue, another word most often in red,...") and we asked participants whether they noticed these regularities. Then we presented each word individually and asked the participants to guess in which of the colours the word was presented most often (objective awareness). The effect is also solidly present for stimuli that participants misclassified in an objective awareness test (Schmidt & De Houwer, 2012b), and intercept analyses show that when the performance of participants is at chance level (no awareness), the learning effect is well above zero (Schmidt & De Houwer, 2019a).

On the other hand, these awareness tests were carried out after the learning phase. Some authors believe that this does not provide strong evidence of unconscious learning. For example, participants may have been aware during learning, but forget when they are probed for awareness. On the other hand, it is not clear whether objective awareness tests exclusively measure explicit knowledge, as implicit knowledge could also bias forced choice guesses (Jiménez et al., 1996). It is also less likely that participants learned the regularities explicitly, but only in a fragmentary way. In the colour-word contingency learning task, the regularities are already simple (word-colour pairings), unlike, for example, in sequence learning where it is possible that only part of a sequence has been learned (Shanks & St John, 1994). In any case, it is clear that awareness in the colour-word contingency learning task is not substantial. Similar results were observed with other learning tasks, such as sequence learning (Destrebecqz & Cleeremans, 2001; Jiménez & Méndez, 1999; Mayr, 1996; Nissen & Bullemer, 1987; Song, Howard, & Howard, 2007; Turk-Browne et al., 2005; Willingham, Nissen, & Bullemer, 1989), artificial grammar learning (Mathews et al., 1989), hidden covariation detection (Lewicki, 1985, 1986; Lewicki et al., 1992), contextual cueing (Chun & Jian, 1998), and the Hebb digits task (Mckelvie, 1987), where effects are observed in unaware participants. Participants can even learn how to control a complex system without being able to answer explicit questions about how the system works (D. C. Berry & Broadbent, 1984, 1988).

In many of our studies, we have not found evidence of a “boost” in the learning effect with increased awareness, although it should be noted that numerical trends suggest that such an advantage exists. On the other hand, other complementary results suggest the existence of benefits with explicit knowledge. For example, in a series of experiments, we explicitly told the participants at the beginning of the procedure the colour in which each word would be presented most often (Schmidt & De Houwer, 2012d). Participants were also instructed to remember these contingencies for a test at the end of the experiment. We observed that this explicit knowledge of contingencies increased the observed contingency effect (although no difference was found in the flanker contingency paradigm; Carlson & Flowers, 1996). Similarly, if the instructed contingencies are incompatible with the actual contingency manipulation (e.g., a participant is told that “move” will be presented most often in green, but it is actually presented most often in blue), the observed contingency effect (i.e., for the “real” contingency) is reduced. Contingency instructions without an actual contingency manipulation did not produce an effect as such, although “simple instruction” effects are observed in other areas (Liefooghe, Wenke, & De Houwer, 2012; Meiran, Pereg, Kessler, Cole, & Braver, 2015; Van Dessel, De Houwer, Gast, & Smith, 2015; Meiran, Liefooghe, & De Houwer, 2017). Similarly, in another study (Schmidt & De Houwer, 2012a), we informed participants in advance of the presence of contingencies between colours and words, but we did not tell them which colour-word pairings would be most common. Instead, participants were asked to try to deliberately learn the contingencies. This also increases the observed learning effect. Similar results were observed in sequence learning. Destrebecqz (2004) observed a larger learning effect of sequential regularities with instructions to learn intentionally.

In another line of research, we observed that working memory resources may be needed to learn and use contingency knowledge (Schmidt, De Houwer, & Besner, 2010). In a modified procedure, participants performed a secondary task of memorizing a series of digits (i.e., they were asked to memorize a certain number of digits for a subsequent recognition test). This secondary task was either easy (2 digits) or difficult (5 digits). The contingency effect was eliminated when participants performed the difficult digit memory task during acquisition (i.e., during training) or testing (i.e., during the transfer phase, where the contingency was absent).

On the other hand, perceptual load does not seem to influence contingency effects in the same way as the working memory load. Cosman, Mordkoff, and Vecera (2016) found that perceptual load did not influence the flanker contingency effect. In particular, participants had to find a target among a set of distractors (E, A, F, or H). A clearly visible flanker (G or S) was presented above or below the set of letters. The flanker was highly predictive of the identity of the target. In the low perceptual load condition, the non-target stimuli were homogeneous (all Os) and distinct from potential targets perceptually, making the target easy to find. In the high perceptual load condition, the non-target stimuli were heterogeneous (U, C, L, P, and J). The contingency effect was robust in both conditions.

Overall, the results obtained with the colour-word contingency learning procedure are consistent with the principles of incidental learning. Any learning that occurs is incidental to the main purpose of the task (colour identification) and learning seems possible without awareness. As in other learning procedures, however, we have observed evidence of top-down influences on the contingency effect, although most of what we observe seems to be primarily implicit in nature.

Stimulus-Stimulus Learning vs. Stimulus-Response Learning

An important question in the statistical learning literature is what participants actually learn about the regularities in this type of incidental learning procedure. For example, in sequential learning, do participants learn the entire sequence, or only parts of it (Perruchet & Amorim, 1992; Perruchet, Bigand, & Benoit-Gouin, 1997)? In this regard, one question we investigated with the colour-word contingency learning procedure is whether participants were learning stimulus pairings, that is, the associations between words and colours. We refer here to *stimulus-stimulus learning.* Alternatively (or jointly), participants could learn the response associated with the task-irrelevant word, which we call *stimulus-response learning.* In other words, a participant who was presented with the word “move” could have learned that the probable colour is blue (stimulus-stimulus) or that the probable response is, for example, the J key (stimulus-response).

To separate these two possibilities, Schmidt and colleagues (2007) used a manipulation with two colours assigned to each response (for applications with the Stroop task, see De Houwer, 2003; Schmidt & Cheesman, 2005). In this procedure, shown in Table II, two colours are assigned to a particular response key (e.g., blue and green with the left key and orange and yellow with the right key). This produces three types of trials. In *stimulus match trials,* the word is presented with the expected colour and response (e.g., “move” in blue, where “move” is presented most often in blue). In *response match trials*, the word is presented in a low contingency colour, but with the high contingency response (e.g., “move” in green, where “move” is rarely presented in green, but the response for green is the same as for blue). In *response mismatch trials*, the word is presented with a low contingency colour and response (e.g., “move” in yellow). The results are presented in Figure 2. Participants responded just as quickly to stimulus match trials as to response match trials, indicating no benefit for high-frequency stimulus pairings. However, participants were slower in response mismatch trials (compared to stimulus match trials and to response match trials), indicating a stimulus-response learning effect.

Table II. Manipulation of Schmidt et al. (2007).

Colour	Word				Response
	move	fall	turn	send	
blue	**9**	1	1	1	F
green	1	**9**	1	1	F
yellow	1	1	**9**	1	J
orange	1	1	1	**9**	J

Note: High contingency trials are indicated in bold.

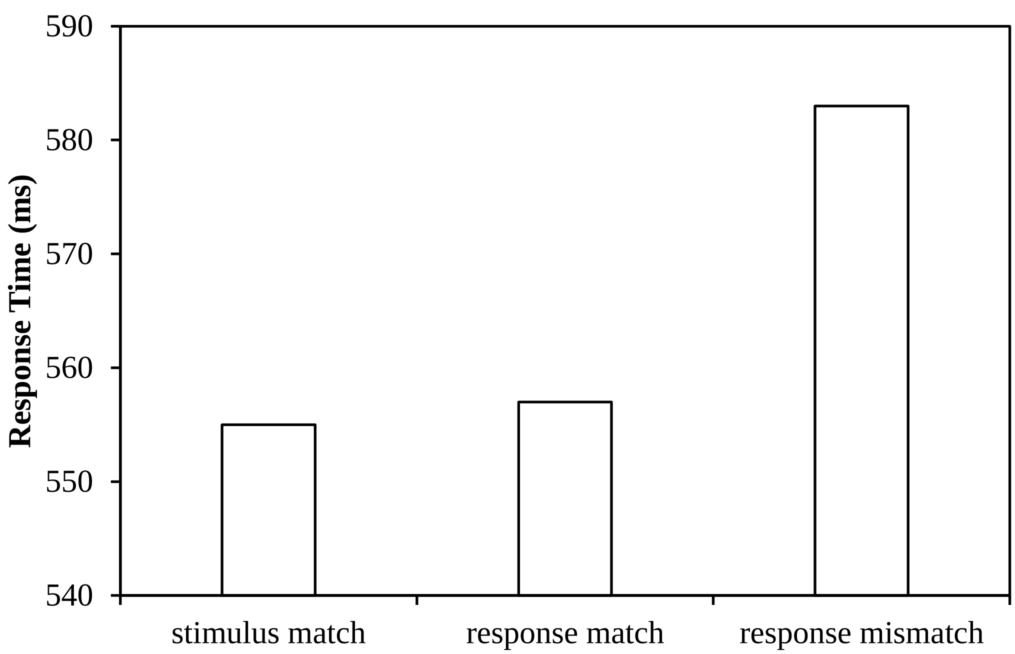

Figure 2. Results of Schmidt et al. (2007), Experiment 4.

A similar stimulus-response learning effect without the effect of stimulus-stimulus match was reproduced in an evaluative conditioning variant of the procedure (Schmidt & De Houwer, 2012b), which will be discussed in a section to follow. Other results are also consistent with stimulus-response learning, such as the finding that the contingency effect is always observed with a large number of non- (or rarely-) repeated target or distractor stimuli (i.e., where stimulus-stimulus pairings are not frequently repeated, but there remains a strong stimulus-response contingency). For example, in one study, distractors predicted positive or negative targets, but not a specific target (Schmidt & De Houwer, 2012b). Conversely, in another study, new words were introduced on each trial. As we will see later, the category of the word was predictive of the response, but the individual stimulus (word-colour) pairs had never been presented before (Schmidt, Augustinova, & De Houwer, 2018).

With the flanker contingency paradigm, Miller (1987) showed a transfer effect. The manipulation is presented in Table III. Three targets were assigned to each response. One flanker was presented most often with the left response and the other flanker was presented most often with the right response. Each flanker was presented most often with two of the targets for each response, but just as often with both targets for the third (C and F in the table). If participants learned only stimulus-stimulus pairings, then the contingency effect should not transfer to these unbiased targets. However, if participants learned contingencies between flankers and responses, then the contingency effect should still be observed for these transfer stimuli. Miller found this transfer effect, which again confirms the notion that participants learn the contingencies between distractors and responses.

Table III. Manipulation of Miller (1987), Experiment 3.

Target	Flanker		Response
	S	T	
A	**30**	2	Left
B	**30**	2	Left
C	**16**	16	Left
D	2	**30**	Right
E	2	**30**	Right
F	16	**16**	Right

Notes: Example stimulus letters only; targets and flankers were chosen randomly from the letters A to W. C and F are the transfer targets. High contingency trials indicated in bold.

Similar discussions have also emerged in research on sequence learning, where some researchers have suggested that participants learn stimulus-stimulus sequences (e.g., Stadler, 1989), others suggested that participants learn response-response sequences (e.g., Willingham, 1999), and still others have argued that stimulus-response association rules are important for sequence learning (e.g., Willingham et al., 1989; for a discussion, see Schwarb & Schumacher, 2010). This debate is more complex in the field of sequential learning, perhaps because sequential regularities are themselves more complex. However, the work has shown that simply maintaining the stimulus sequence or the response sequence is not enough to produce the learning effect when the stimulus-response rules change (Willingham et al., 1989). As with the colour-word contingency learning procedure, stimulus-response associations seem, at a minimum, to be the most powerful factor in producing robust learning effects. Overall, the results suggest that participants learn what response to expect, based on distractors. The absence of a stimulus-stimulus learning effect indicates either (a) that participants are not learning word-colour pairings, or (b) that they are learning word-colour pairings, but this does not produce a robust effect on response time.

Learning Rate and Frequency

Many may think of a "learning effect" as something that slowly emerges through multiple learning blocks. A moderate upward trend with more learning is apparent, but the colour-word contingency learning effect appears almost immediately from the start of training. For example, even with relatively small blocks of 18 trials, a contingency effect is already observed in the very first block in Schmidt, De Houwer, and Besner (2010). Similar results have been observed in other articles (e.g., Lin & MacLeod, 2018; Schmidt & De Houwer, 2016b). Figure 3 shows the data from Lin and MacLeod, divided into 18 blocks of 48 trials. As can be seen in the figure, the learning effect was consistently present throughout the learning phase (first six blocks). This rapid acquisition is reminiscent of the learning observed in other learning procedures. For example, learning effects were observed after a single consistent pairing in a hidden covariation detection task (Lewicki, 1985, 1986; Lewicki et al., 1992). Similarly, sequence learning effects were found after short training procedures (Nissen & Bullemer, 1987) and equally rapid learning was observed in the Hebb digits task (Mckelvie, 1987).

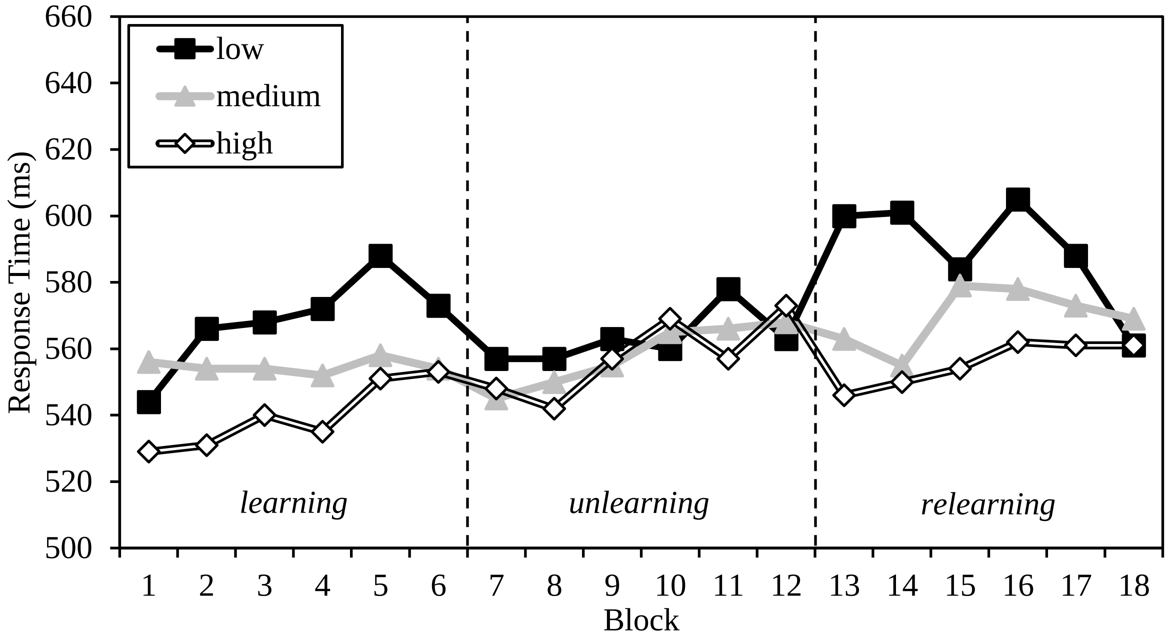

Figure 3. Results of Lin et MacLeod (2018), Experiment 2.

Also, adaptations to changes in contingencies occur very quickly. For example, if the initial contingencies are eliminated after a learning phase (i.e., the same words are now presented equally often in all colours), then unlearning of the original contingency is quickly observed (Lin & MacLeod, 2018; Schmidt & De Houwer, 2016b; Schmidt et al., 2010). Although the effect is not entirely eliminated, the difference between the (previously) high and low contingency trials decreases rapidly towards zero, as also shown in Figure 3 (six blocks in the middle). In the same vein, if the initial contingency is reintroduced, we observe very rapid relearning (Lin & MacLeod, 2018; Schmidt & De Houwer, 2016b), as also shown in Figure 3 (last six blocks). Along with other results that will be discussed later in this article, these results were taken as evidence of a high learning rate, where recent events matter much more for current behavior than older events.

In the context of recent work (Schmidt, De Houwer, & Moors, 2020), we explored whether substantial overlearning of contingencies eventually leads to the stability of contingency effects. For example, if participants repeatedly learn the regularity between the word “move” and the colour blue, will the facilitating effect of the regularity persist throughout a subsequent unlearning phase? Will it be the same throughout a counter-conditioning phase where a new regularity is introduced (e.g., “move” is now most often presented in green)? Our results with multi-day training studies suggest some lasting influences of overtraining, as well as a powerful effect from recent experiences. In other words, the initial contingency did not create a stable and unalterable habit.

Another issue that has been addressed with the colour-word contingency learning paradigm is the extent to which the learning effects produced by the paradigm are due to facilitation (speeding) on high contingency pairings, interference (slow down) on low contingency trials, or a combination of both. Lin and MacLeod (2018) used a control condition (see also, Schmidt & Besner, 2008) with medium (chance) contingencies, where the medium contingency words were presented equally often in all colours. The data from their Experiment 1a are presented in Figure 4. In several experiments, they observed both facilitation and interference with this control (although not directly tested, the results of Hazeltine & Mordkoff, 2014, suggest the same pattern).

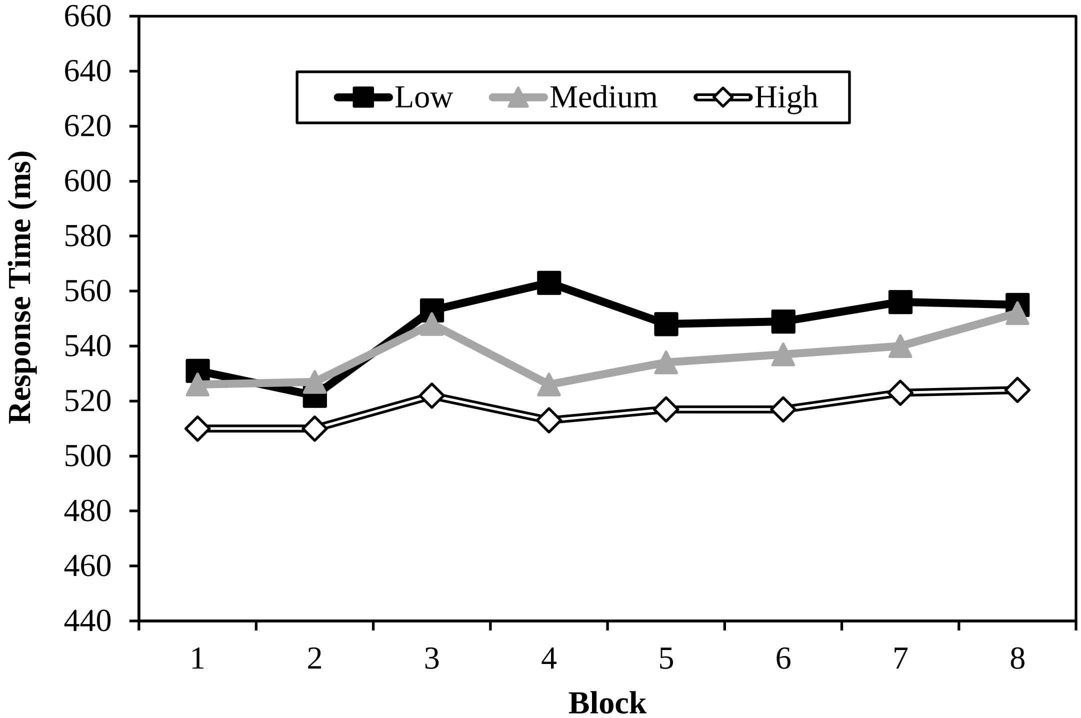

Figure 4. Results of Lin et MacLeod (2018), Experiment 1a.

Other results seem to be consistent with the notion of facilitation and interference. For example, increasing the contingency proportions (e.g., from 70% high contingency pairings to 90%) increases the contingency effect (with colour-word contingency learning, Forrin & MacLeod, 2018; and with flanker contingency learning, J. Miller, 1987). Miller's data suggest that a stronger manipulation accelerates both high contingency trials and slows down low contingency trials, but he did not directly compare high and low contingency trials separately. Forrin and MacLeod only found a slowdown for low contingency trials.

In similar research, Schmidt and De Houwer (2016a) adjusted the typical experimental design to produce not only high and low contingency trials, but also three other types of controls, of "medium contingency". The relative frequencies of the word and colour combinations used in Experiment 1 of the latter work are presented in Table IV. It should be noted that high contingency pairings (the 9s in Table IV) are frequent, low contingency pairings (the 1s in Table IV) are rare, and the remaining three conditions occur with an intermediate (or chance) frequency. In *biased word* trials (e.g., “give” in grey), the word was “predictive” of a colour (e.g., “give” is presented most often in purple), but only occurs with an intermediate frequency in the currently presented colour (e.g., grey). The colour of these trials is “non-predictive” (e.g., grey is presented as often with each of the three words). *Colour-biased* trials reflect the opposite situation, with a “predictive” colour and a non-predictive word (e.g., “make” in purple). Finally, neither the word nor the colour were informative on *unbiased* trials (e.g., “make” in grey).

Table IV. Adapted manipulation of Schmidt and De Houwer (2016a).

Colour	Word		
	give	hear	make
purple	9	1	5
orange	1	9	5
grey	5	5	5

The data are presented in Figure 5. Interestingly, we observed both facilitation for high contingency trials and interference for low contingency trials compared to all three controls. No differences were observed between the three types of medium contingency trials. This result was seen as evidence against the idea that anticipating a response entails a cost when the actual response required is different. For example, if the word is “give”, the answer should probably be purple. If this expectation for the purple response is incorrect (e.g., the colour is grey), we might imagine that this would produce a cost (interference). However, we did not observe this. The idea that the response is slower when a stimulus is not presented in the expected pairing was therefore not supported. Instead, we interpreted these results as indicating that participants are simply sensitive to the frequency (and/or proportion) of previous encounters with each stimulus combination. That is, participants accelerate significantly with frequent pairings, accelerate moderately with moderate frequency pairings, and accelerate slightly with infrequent pairings. This suggests that “interference” in low contingency trials actually reflects “less facilitation”. Supporting this notion further, a second experiment showed that participants were, at least numerically, *slower* to respond to trials with new words that were presented only once each (no past experience with pairings) compared to low contingency trials (a few experiences, but infrequent).

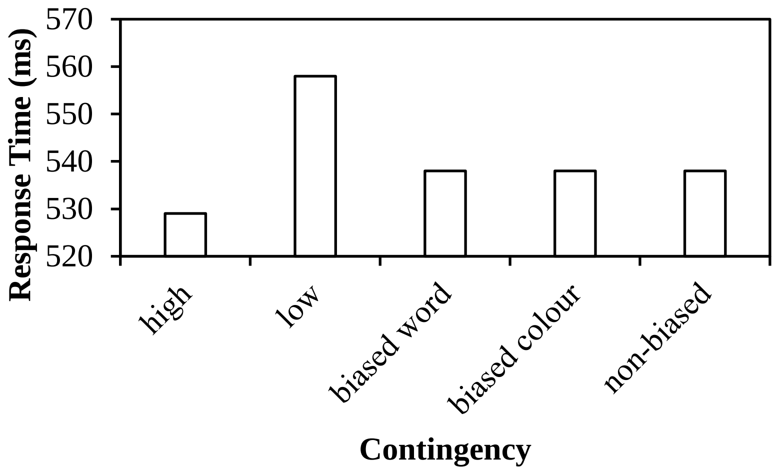

Figure 5. Results of Schmidt and De Houwer (2016a), Experiment 1.

Of course, we know that real interference occurs in conflict paradigms like the Stroop task (Stroop, 1935; for a review, see MacLeod, 1991). For example, the fact that the word “blue” is associated with a naming response, “blue”, makes participants slower and more prone to errors if the target colour is red. This interference relative to a neutral control is also observed for words recently acquired in a foreign language (e.g., Altarriba & Mathis, 1997). It is not clear what makes the results of colour-word Stroop paradigms and colour-word contingency learning different in this regard. In any case, contingency learning results are consistent with the well-understood principles of training and automaticity: the more often a participant has seen a stimulus and given the same response to it, the faster they become (Grant & Logan, 1993; Logan, 1988). And incidental learning is quick. If there is a simple regularity that can be learned incidentally, then the regularities will begin to influence behavior with surprisingly little training. Contrary to what is observed in some forms of implicit learning (Cleeremans & McClelland, 1991; Misyak, Christiansen, & Tomblin, 2010), learning emerges immediately during training. This result is probably due to the small number of regularities to be learned (Van Den Bos & Poletiek, 2008).

Category Learning

Learning, especially human learning, is not always specific to a stimulus. Instead, we can often learn more abstract regularities (e.g., Brady & Oliva, 2008; Emberson & Rubinstein, 2016). It is not always necessary to refer to specific stimuli to learn a conceptual relationship and learning for some stimuli can often be transferred to those that are related. To determine whether categorical learning can occur in a purely incidental manner, Schmidt, Augustinova, and De Houwer (2018) explored whether the colour-word contingency effect can generalize, beyond the individual items, to more abstract categorical regularities. Instead of having a small set of frequently repeated words (e.g., 3 words, each presented hundreds of times), a large list of task-irrelevant words was presented. Each word belonged to one of three categories (professions, verbs, or animals). Each word was presented only once, but words in a given category were often presented in a given colour (e.g., professions most often in blue, verbs most often in red, etc.). Thus, halfway through the experiment, if the word “doctor” was introduced to participants, they had no previous experience of the word in any of the three target colours. However, they had previously seen other words related to professions in blue. We observed a categorical learning effect, with faster responses and fewer errors to high category-colour contingency trials (e.g., “doctor” in blue) than to low-contingency trials (e.g., “doctor” in red).

The learning effect at the category level was smaller and was not observed consistently for all participants, unlike the results with a typical stimulus-specific manipulation. This probably makes some sense from a conceptual point of view. The regularity to learn is much more abstract. Each new stimulus encountered has no direct link with the high contingency response, but only an indirect link via a category level overlap with previously experienced stimuli.

Similar learning at the category level can occur during sequential learning. For example, in two series of studies, participants received a series of images and the experimenters asked them either to detect image repetitions (i.e., the same image twice in a row; Brady & Oliva, 2008) or to simply passively look at the images (Emberson & Rubinstein, 2016). The images followed a predictable sequence of categories. That is, the individual images did not have a predictable sequence, but the categories did (e.g., fish followed by dogs, flowers followed by birds, etc.). These sequences at the category level were learned by the participants (explicit contingency judgments). As with the colour-word contingency learning procedure, however, Emberson and Rubinstein found that participants were more sensitive to stimulus-specific contingencies than to category-specific contingencies.

Overall, all the results discussed in this section are consistent with the basic principle of statistical learning that we aim to detect consistency in our environment. Exact matches between stimuli and responses are the easiest to detect, but it is equally important to try to learn the generalized “rules” of the environment (Badre, Kayser, & D’Esposito, 2010; Botvinick, 2008), which are often more abstract (e.g., different stoves may look slightly different, but we do not need to learn, for each individually, that touching a hot burner is unpleasant). Other recent research has also investigated categorical learning in the context of more transitory binding effects, where category-level learning has also been observed (e.g., Allenmark, Moutsopoulou, & Waszak, 2015; Horner & Henson, 2011).

Evaluative Learning

Evaluative conditioning (for a review, see Hofmann, De Houwer, Perugini, Baeyens, & Crombez, 2010) consists in the observation of a change in the preference of an initially neutral stimulus after the latter has been associated with a non-neutral stimulus (De Houwer, 2007). In a typical evaluative conditioning procedure, a neutral conditioned stimulus (CS) is associated a number of times with a positive or negative unconditioned stimulus (US). For example, in flavour conditioning (Garcia & Koelling, 1966; Rozin & Zellner, 1985), one neutral taste can be mixed with a pleasant taste and another neutral taste can be mixed with an unpleasant taste. After conditioning, the first neutral taste is generally evaluated more positively than the second. In other words, the valence (positive vs. negative) of a US is transferred to the CS with which it is associated. Similarly, a neutral image that was frequently presented with a smiling face is generally rated more positively than a neutral image that was paired with an angry face (e.g., Baeyens, Eelen, Crombez, & van den Bergh, 1992; see also, Levey & Martin, 1975).

Evaluative conditioning experiments usually involve explicit learning. To study evaluative conditioning in a more incidental learning environment, Schmidt and De Houwer (2012b; for a very similar task, see Greenwald & De Houwer, 2017) developed a variant of an evaluative conditioning procedure based on the colour-word contingency learning procedure. On each trial, the participant received a nonword prime (e.g., “alsan”). The prime was followed by a positive or negative target word (e.g., “flowers” or “guns”). The task of the participant was to decide whether the target was positive or negative. Importantly, some nonwords were presented most often with positive targets and other nonwords were presented most often with negative targets. Participants responded faster and with fewer errors to targets when the nonword was presented with the expected valence versus the unexpected valence.

Gast, Richter, and Ruszpel (2020) reproduced these observations (see also unpublished data from Bar-Anan, Sarzynska, and Balas: https://osf.io/rtk2n/). We also measured explicit evaluations (the typical dependent measure of an evaluative conditioning experiment) of nonwords after learning. Nonwords that were frequently presented with positive targets were rated more positively than those presented frequently with negative targets (cf., Gast et al., 2020). This effect on explicit ratings was also strongly correlated with response time and error contingency effects. In Experiment 2, we also assessed contingency awareness (for a correction, see Schmidt & De Houwer, 2019a). We observed that participants had little or no awareness of contingencies in an objective awareness test, with relatively low accuracy in guessing which nonwords were most often presented with positive stimuli and which were most often presented with negative stimuli. Few participants reported being aware of the regularities (subjective awareness). Response time, error, and rating contingency effects did not depend on consciousness, whether assessed at the subject level (i.e., whether the effect persists if the participant guesses chance) or at the item level (i.e., whether the effect persists for the words that the participants incorrectly guessed in the objective awareness test; see Baeyens, Eelen, & Van den Bergh, 1990; Pleyers, Corneille, Luminet, & Yzerbyt, 2007; Stahl & Unkelbach, 2009). Thus, learning seems to be primarily unconscious.

Greenwald and De Houwer (2017) subsequently conducted similar studies with letter strings for CSs and valenced words (USs) as targets. Interestingly, they found evidence of unconscious conditioning with masked primed stimuli. They also found evaluative conditioning effects with clearly visible prime stimuli, but these latter effects appeared to be more awareness-dependent. Gast, Richter, and Ruszpel (2020) also added a few trials with a neutral target stimulus in their Experiment 2. In these trials, participants had to decide whether the neutral target appeared relatively more positive or more negative, as in the affect misattribution procedure (AMP ; Payne, Cheng, Govorun, & Stewart, 2005). During the learning phase, they found more positive responses for neutral targets preceded by nonwords most often associated with positive targets than nonwords most often associated with negative targets.

So far, some results suggest that evaluative conditioning can occur without awareness, which is a major topic of debate in the evaluative conditioning literature (for a review, see Sweldens, Corneille, & Yzerbyt, 2014; for a meta-analysis, see Hofmann et al., 2010); however, there are currently inconsistencies in the published work. The size or presence of an explicit post-learning rating effect in the colour-word contingency learning task also seems unclear.

Temporal Contiguity

Contingency (or covariation) learning is important for understanding the relationship between events in our world. Going back at least as far as Hume (1969), we recognized the importance of the *temporal contiguity* between events in causal perception (Michotte, Miles, & Miles, 1963) and learning (for a review, see Buehner, 2005; Gallistel, Craig, & Shahan, 2019). To use a simple example, if you press a “mystery button” and a light in the room comes on almost immediately, you are likely to attribute the light to the button press. Conversely, if nothing happens immediately after pressing the button but the light turns on a minute later, there is little chance that you will attribute the button press as the cause of the light turning on. The maintenance of a close temporal contiguity between related information has also been studied in an educational context (Khacharem, Trabelsi, Engel, Sperlich, & Kalyuga, 2020; for a review, see Ginns, 2006).

Schmidt and De Houwer (2012c) explored the extent to which contingency effects depend on the *temporal contiguity* between the presentation of the predictive stimulus and the target stimulus. We manipulated the delay between the appearance of predictive nonwords and target colour words in a series of studies. In our first three studies, the distractor and target stayed on the screen together, but they appeared with different Stimulus Onset Asynchronies (SOAs). In Experiment 3, the SOAs were negative, meaning that the distractor appeared after the target. In Experiment 4, the duration of the distractor presentation was fixed, and we manipulated the Inter-Stimulus Interval (ISI), the time between the distractor offset and the appearance of the target. Overall, the results indicate that contingency effects are apparently robust for a range of different temporal contiguities. In other words, the contingency effect does not seem to vary in magnitude, notably with a wide range of asynchronies (SOA) or inter-stimulus intervals (ISI), between −350 and 1200 ms SOA.

In related work on action-effect learning, Elsner and Hommel (2004) first asked participants to respond to the arrows (pointing to the left or right) with a left or right key. Subsequently, each response was more frequently followed by a sound of a different pitch (i.e., one sound most often after a left response and another sound of a different pitch most often after a right response). In this case, learning was between a response and an outcome, rather than between a stimulus and a response. In a second phase, participants responded to the sounds, either with responses that were compatible with the initial training (e.g., the response for each sound was the same as the response that was generally followed by that sound) or incompatible. During the test phase, responses were faster and more accurate for compatible pairings. The authors also manipulated the asynchronies (50, 1000, and 2000 ms) and found that the learning effect was only eliminated with very long delays (2000 ms).

Interestingly, these results are very different from those of conflict paradigms, such as the Stroop task, where subtle variations in temporal contiguity significantly reduce interference effects (e.g., Glaser & Glaser, 1982). The results are also very different from temporal contiguity studies in causal perception research, where very short time frames are required for causal perception (e.g., Michotte et al., 1963). Although the work is currently limited, the results suggest that predictive cues have more lasting influences across intervals. This may make some sense. In the case of Stroop, for example, participants actively try to avoid reading distracting words in order to avoid interference. In the colour-word contingency learning paradigm, on the other hand, the word "distractors" are informative. It is therefore useful to keep the predicted response in memory when the words are informative about the likely response. This also concerns debates in the memory literature dealing with the inherent role of temporal contiguity in encoding, that is, whether memories are intrinsically encoded in a temporal sequence (Howard & Kahana, 2002; Howard, Shankar, Aue, & Criss, 2015) or whether the items are related to each other in a way that is considered useful for later retrieval (Hintzman, 2016).

Compound Cues

While some older theories of learning assumed element learning, that is, when several stimuli are presented together learning is updated separately for each stimulus individually (elemental; Mackintosh, 1975; Pearce & Hall, 1980; Rescorla & Wagner, 1972), other theories assume that learning is based on stimulus configurations (configural; Kinder & Lachnit, 2003; Pearce, 2002; Soto, Gershman, & Niv, 2014; Wagner, 2003). In studies with animals and humans under explicit learning conditions, for example, biconditional discrimination studies examine whether participants can learn contingencies based on a combination of two stimuli (Lober & Lachnit, 2002; Saavedra, 1975).

Other work has focused on incidental learning with more than one task-irrelevant cue. In an article by Mordkoff and Halterman (2008) using a variant of the flanker contingency paradigm, individual task-irrelevant flankers were not predictive of the responses, but their combinations were. Their manipulation is presented in Table V. For example, for one participant, upright pound signs (#; which used only horizontal and vertical lines) in blue and tilted pound signs (which used 45-degree tilted lines) in yellow were most often presented with the left response, while tilted pound signs in blue and upright pound signs in yellow were most often presented with the right response. Thus, neither the colour nor the type of pound sign is informative about the response itself, but they are in combination. In this particular task, participants were also required to respond to compound targets (e.g., red square or green diamond with the left key and red diamond or green square with the right key). As in Experiment 3 of Miller (1987, see Table III), there were inducing targets and diagnostic targets, but this detail is less important for current purposes. Participants produced a compound contingency learning effect, with faster responses to high contingency compound cues compared to low contingency compound cues.

Table V. Manipulation of Mordkoff and Halterman (2008).

Target	Flanker Orientation / Colour				Response
	#-upright		#-tilted		
	blue	yellow	blue	yellow	
☐ in red	**4**	0	0	**4**	Left
◇ in green	**2**	2	2	**2**	Left
☐ in green	0	**4**	**4**	0	Right
◇ in red	2	**2**	**2**	2	Right

Note: The high contingency trials shown in bold.

In a recent study by Schmidt and Lemercier (2019), participants responded to the colour of words that were presented in one of two fonts. In this experiment, the targets corresponded to a single dimension (colour). An example of the design of their Experiment 1 is shown in Table VI. The distracting words were, at the task scale, only moderately predictive of two of the four target colours, while the fonts were not informative at all about the colour response. However, the combination of a word in a given font were highly predictive of the target response. For example, the word “brown” in Georgia font may have been presented most often in brown, while the word “brown” in Arial font may have been presented most often in blue.

Table V1. Experiment 1 contingency manipulation of Schmidt and Lemercier (2019).

	Font / Word							
Colour	italic Georgia				roman Arial			
	brown	blue	green	red	brown	blue	green	red
brown	9	1	1	1	1	9	1	1
blue	1	9	1	1	9	1	1	1
green	1	1	1	9	1	1	9	1
red	1	1	9	1	1	1	1	9

Incidentally, this particular experiment involved a manipulation of congruency, with congruent trials (e.g., “blue” in blue) and other incongruent trials (e.g., “blue” in red). The study was also partially designed to answer some questions about context specificity in attentional control (e.g., see Corballis & Gratton, 2003; Crump, Gong, & Milliken, 2006), for which no evidence was found. In any case, the experiment also allowed for a test of compound cue contingency learning. Indeed, participants reacted more quickly to high contingency trials, such as “brown” in blue in Arial font, than to low contingency pairings, such as “red” in blue in Georgia font. It should be noted that these types of trials were matched for congruency (all incongruent) and proportion congruency (all mostly incongruent in the context), while the other congruent and mostly congruent trials are of less interest in the present discussion.

Overall, the two lines of research mentioned above demonstrate that not only unique stimuli, but also their combinations, can produce robust learning. Similar learning with multiple cues is also observed in other types of learning studies. For example, in a sequence learning task, it is possible to observe second-order conditioning (e.g., Cohen, Ivry, & Keele, 1990; Reed & Johnson, 1994). Specifically, the next stimulus in a sequence is not predictable based on the immediately preceding stimulus (e.g., Stimuli 1, 2, and 3 are equally likely after Stimulus 4), but the next stimulus is perfectly predictable based on the last two stimuli (e.g., after Stimulus 1 and then 4, the next stimulus is always Stimulus 3, whereas after Stimulus 2 then 4, the next stimulus is always Stimulus 1, etc.).

Interestingly, participants can not only use stimulus conjunctions to predict future responses (related to occasion setting; e.g., see Fraser & Holland, 2019; Holland, 1992), but this compound cue knowledge can be acquired and can influence behavior relatively automatically in an incidental learning environment.

Cue Competition and Incidental Learning

Participants can learn regularities based on compound cues. However, in some situations, the simultaneous presentation of two or more stimuli produces *cue competition*. *Overshadowing*, for example, occurs when learning the relationship between a stimulus, often called Stimulus X, and a matched outcome is altered by the simultaneous presentation of another stimulus, often called Stimulus A (Pavlov, 1927). For example, while a rat can normally learn to press a lever for a food reward whenever a sound is played, it may not learn the relationship between sound and food when a light (A) and sound (X) are always presented together as predictors of food. *Blocking* occurs when the initial learning of the relationship between Stimulus A (e.g., light) and an outcome interferes with the subsequent learning of the relationship between Stimulus X (e.g., sound) and the same result when A and X are presented together (Kamin, 1969).

There are a number of hypotheses to explain cue competition phenomena such as overshadowing and blocking (e.g., Mackintosh, 1975; Pearce & Hall, 1980; Rescorla & Wagner, 1972; Sutherland & Mackintosh, 1971), but the key point is that knowing the relationship between Stimulus A and the outcome hinders learning the relationship between Stimulus X and the outcome. Typical studies of cue competition in humans involve rather explicit learning objectives (e.g., Chapman & Robbins, 1990; Dickinson, Shanks, & Evenden, 1984; Gluck & Bower, 1988; Le Pelley & McLaren, 2001). Thus, Schmidt and De Houwer (2019b) used the colour-word contingency learning paradigm to examine whether overshadowing and blocking effects can be observed during incidental learning (i.e., where deliberate learning is not the goal of the task). For "Stimulus A" and "Stimulus X", we used neutral words and shapes (respectively or vice versa), with a target print colour. This allowed us to have: (a) word-only trials (with coloured words, but no shapes), (b) shape-only trials (coloured shapes, but no words), and (c) compound-cue trials (with both a word and a shape together in a colour).

In one overshadowing experiment, participants saw words and shapes presented in colour (overshadowing) or only coloured words (words-only) or only coloured shapes (shapes-only). As presented in Table VII, each word, shape, or word-shape compound was most often presented in a colour, as in the typical colour-word contingency learning paradigm. After the training phase, there was a test phase, during which we determined whether there was a contingency effect for words and/or shapes. The results of this test phase are shown in Figure 6. We did not observe an overshadowing effect. Instead, we observed contingency effects that were just as large for the dimensions that were learned in compounds as for the stimuli that were learned on their own. Similarly, in another experiment, we did not observe blocking. The results revealed equally large contingency effects for both the initially trained dimension ("blocker"; for example, words) and the second dimension ("blocked"; e.g., shapes). Interestingly, cue competition effects were only observed in response times or errors when we, at the beginning of the experiment, explicitly asked participants to try to learn contingencies (or when we tested less automatic explicit contingency judgments). This is consistent with another study that tested the effects of automatic cue competition after intentional training (Morís, Cobos, Luque, & López, 2014) and failures to observe blocking in purely incidental learning (Beesley & Shanks, 2012).

Table VII. Manipulation of Schmidt and De Houwer (2019b), Experiment 1.

Target	Word and/or Shape								
	look	take	jump	□	○	△	look+□	take+○	jump+△
Training									
words-only									
blue	**8**	1	1						
red	1	**8**	1						
green	1	1	**8**						
shapes-only									
blue				**8**	1	1			
red				1	**8**	1			
green				1	1	**8**			
compound-cues									
blue							**8**	1	1
red							1	**8**	1
green							1	1	**8**
Test									
all groups									
blue	**1**	1	1	**1**	1	1			
red	1	**1**	1	1	**1**	1			
green	1	1	**1**	1	1	**1**			

Note: High contingency trials shown in bold.

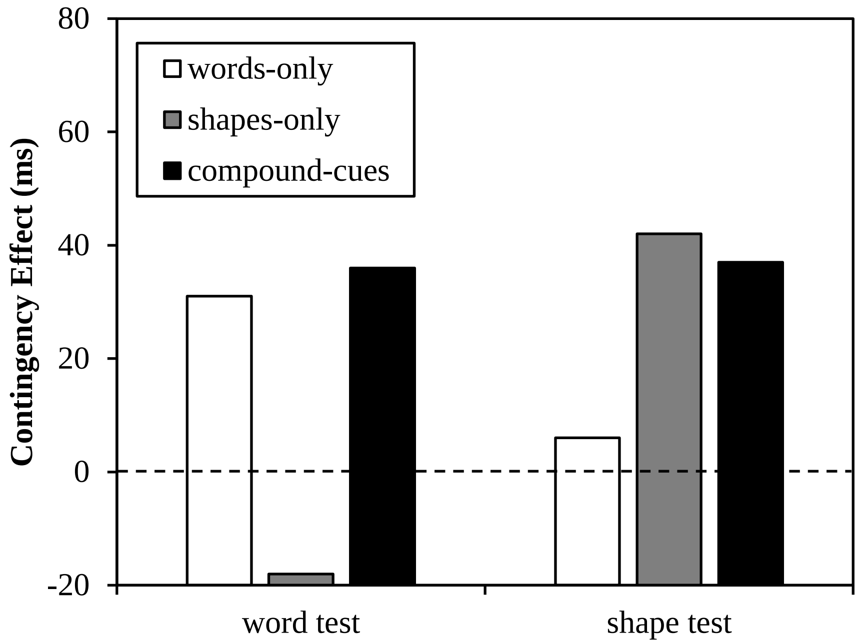

Figure 6. Results of the test phase of Schmidt and De Houwer (2019b), Experiment 1.

Collectively, the results suggest that cue competition effects, such as blocking and overshadowing, require explicit reasoning about the contingencies of the task (e.g., see De Houwer, Beckers, & Vandorpe, 2005; Lovibond, 2003; Vandorpe & De Houwer, 2005). When learning is purely incidental and we test the automatic influences of cue competition (e.g., in response times and errors), cue competition does not appear to be present. Instead, robust learning is observed even for “overshadowed” or “blocked” stimuli.

Conceptually, these results are interesting because they suggest that cue competition effects are not an automatic result of association formation, as many conceptual theories of cue competition might suggest. For example, in the Rescorla-Wagner model (Rescorla & Wagner, 1972), association strengths are not adapted when the result is already expected. Instead, the results suggest that cue competition effects result from explicit reasoning about regularities (e.g., “I already know that Stimulus A predicts the outcome; now I see Stimuli A and X with the outcome; so, I do not know if Stimulus X helps at all”). This is, in fact, a rational conclusion.

Learning and Binding

Another important issue frequently discussed in the literature on statistical learning is the relationship between binding and learning. Particularly in the language learning literature, many influential models have explored how information is analyzed in units (e.g., how words are analyzed from a continuous speech stream). These statistical learning models detect clusters or chunks of related information (Frank, Goldwater, Griffiths, & Tenenbaum, 2010; French, Addyman, & Mareschal, 2011; Giroux & Rey, 2009; Orbán, Fiser, Aslin, & Lengyel, 2008; for reviews, see Perruchet & Vinter, 1998; Perruchet, 2019; Perruchet & Pacton, 2006; Thiessen et al., 2013), unlike other models that learn transition probabilities (e.g., Mirman, Estes, & Magnuson, 2010; for a comparison, see Perruchet & Peereman, 2004). Such theories vary in their assumptions about how clusters are created (e.g., activation of competitive segments, Bayesian inference, etc.), but assume that discrete representations of associated information are stored. Chunking and learning can be seen as two fundamentally distinct processes, but they do not need to be (Thiessen et al., 2013). A related question is to what extent the influence of recent bindings on behavior is identical or dissociable from the influence of regularities at the task scale.

Binding refers to the link between stimulus experiences and responses in memory traces (Hommel, 1998, 2004; Hommel, Musseler, Aschersleben, & Prinz, 2001; Logan, 1988). Recent events have particularly large influences on current behaviour (Grant & Logan, 1993). Binding procedures investigate the influence of recent stimulus-response events. For example, in the distractor-response binding paradigm (e.g., Frings, Rothermund, & Wentura, 2007; Rothermund, Wentura, & De Houwer, 2005), participants identify a target (e.g., the colour of a word) while ignoring a distracting stimulus (e.g., the word itself). The repetition or alternation of the stimulus and/or the response from one trial to another produces a *binding effect,* as illustrated in Figure 7.

Specifically, when the target (and therefore the response) is repeated, also repeating the word (complete repetition) leads to much faster responses compared to trials where the word changes (partial repetition). On the other hand, when the target/response changes, repeating the word (partial repetition) produces a slight cost compared to trials where the word changes (complete alternation). It is the interaction between stimulus relation (repetition vs. alternation) and response relation (repetition vs. alternation) that we call the binding effect.

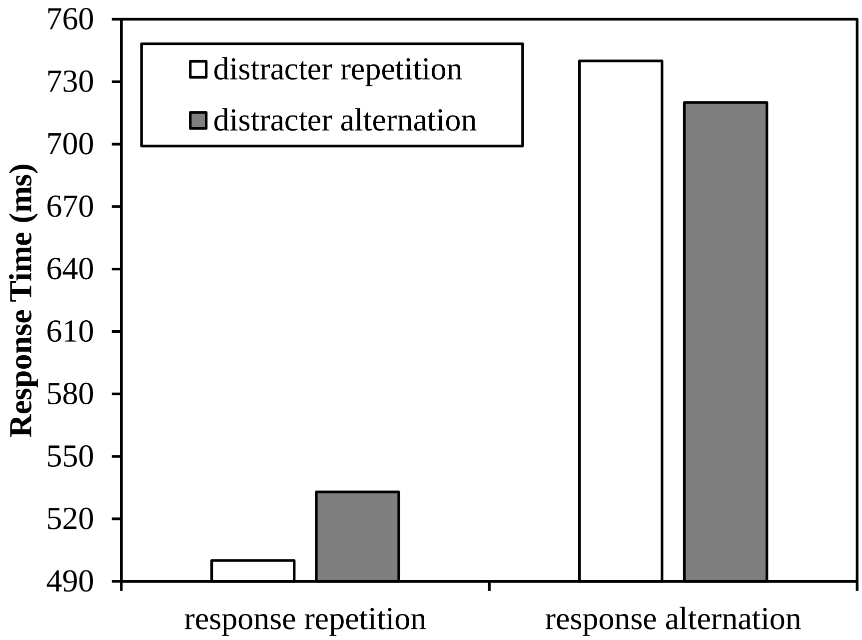

Figure 7. Results of Frings et al. (2007), Experiment 1a, illustrating the standard binding interaction.

It is often argued that binding effects are caused by "event files" that are conceptualized as temporary links between stimuli and responses in short-term memory (Hommel, 1998, 2004; Hommel et al., 2001). Because these event files break down quickly (Stoet & Hommel, 1999), the effects are short-lived, influencing performance only in trials immediately (or almost immediately) following encoding. This contrasts with learning effects, which are often conceptualized in terms of associations stored in long-term memory and are gradually reinforced by learning (Colzato, Raffone, & Hommel, 2006; Hommel & Colzato, 2009). However, in a computational modeling paper, Schmidt, De Houwer, and Rothermund (2016) suggested that binding and learning effects could instead be conceptualized as, respectively, the short- and long-term consequences of the same learning processes (see also, Frings et al., 2020). For example, after seeing “move” in blue, the link between “move” and blue is reinforced (e.g., with a new memory trace or an augmented associative link). This will facilitate, for example, the response to the next trial if the same stimuli (“move” in blue) are presented (binding effect). Thus, in this conceptualization, binding effects are due to the powerful influence of a recent update in learning, while learning effects are simply due to an accumulation of these updates over several trials. In other words, the cumulative effect of many individual bindings is the contingency effect. Indeed, binding effects are “confounded” with contingencies. For example, complete repetitions of a high contingency stimulus (e.g., “move” in blue) will occur much more frequently than complete repetitions of a low contingency stimulus (e.g., “move” in red). Indeed, if “move” is frequently presented in blue, this makes a sequence of “move” in blue followed by “move” in blue relatively common. However, if “move” is rarely presented in red, it will be extremely rare to see “move” in red twice in a row.

Two recent articles (Giesen, Schmidt, & Rothermund, 2020; Schmidt, Giesen, & Rothermund, 2020) examined whether contingency learning effects and short-term binding effects could be coherently explained by a single mechanism. Using different techniques, we investigated whether the colour-word contingency learning effect can be broken down into binding effects from a number of previous trials (e.g., Trial $n-1$, $n-2$, etc.). In other words, we sought to determine whether the “learning effect” is more than just the joint influence of many recent bindings (for an earlier but suboptimal approach to the same question, see Schmidt et al., 2010). The assumed relationship is a power curve, as shown on the left in Figure 8. Controlling for binding condition (i.e., complete repetition, partial repetition, etc.) for trials with a longer and longer lag (e.g., $n-1$, $n-1$ and $n-2$, $n-1$ to $n-3$, etc.) should leave less and less room for contingency. Recent events should have a particularly large influence on performance, as these memory traces are the most accessible. The contingency effect will therefore greatly decrease after controlling for the $n-1$ binding effect, a little more after controlling for $n-1$ and $n-2$ binding effects, etc. On the other hand, if binding effects do not survive more than one or two trials and there is a simple effect of continency, we would anticipate a curve as shown to the right of Figure 8. If the contingency and binding effects are completely orthogonal, we would anticipate a straight line (i.e., no reduction in the contingency effect). Although somewhat more complicated than presented in Figure 8, our results are consistent with the idea that the majority of the contingency effect can be explained by an accumulation of many bindings. Note that the rapidly decreasing influence of older and older events is also consistent with the rapid learning rates observed in the task: large adjustments to the just encountered stimuli should produce rapid learning and also rapid adjustment to changes in contingencies.

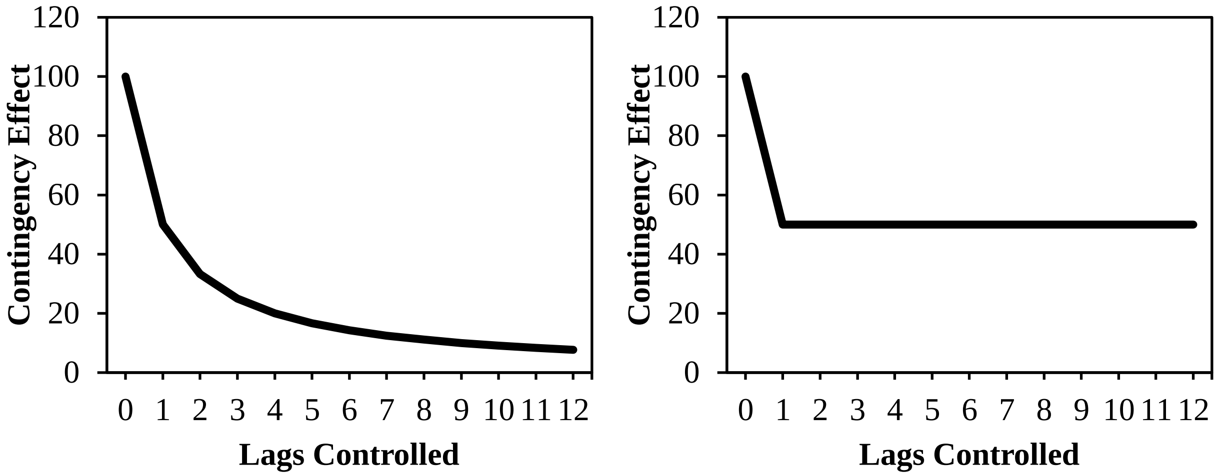

Figure 8. (left) Relation between learning and binding according to an integrative view. Controlling for previous-trial bindings reduces the remaining main effect of contingency. Recently coded events have more powerful influences on performance than older memories. (right) Same relation according to a non-integrative view.

Other research, however, suggests potential dissociations between learning and binding effects. For example, a series of studies by Colzato, Raffone, and Hommel (2006; see also, Hommel & Colzato, 2009) showed that binding effects between stimuli (but not between stimuli and responses) did not show modulations of binding effects based on the presence or absence of existing or recently learned associations between stimuli. That is, there are no interactions between binding and learning effects. The authors assumed that if binding and contingency effects were due to the same mechanisms, then the two would interact (but see, Schmidt, Giesen, et al., 2020). They therefore interpreted their results as evidence of different underlying mechanisms of learning and binding.

In the same context, another series of studies by Moeller and Frings (2017a) is particularly interesting. These authors used a variant of the flanker contingency paradigm in which flankers were presented in advance of the targets (sometimes called the temporal flanker paradigm). In one block, flankers predicted targets (as in J. Miller, 1987) and a contingency effect was measured. In another block, flankers were not predictive of targets and a binding effect was measured. Interestingly, binding effects were larger when flankers were oriented horizontally with targets (i.e., flanker to the left and right of the target) than when they were oriented vertically (i.e., flanker above and below the target). This was interpreted as resulting from a stronger binding between horizontally organized letters and better filtering of vertically organized flankers. The contingency effect, however, was not influenced by the organization of the flankers. In addition, the authors found larger contingency effects with a long delay between the appearance of flankers and the target, but a larger binding effect with a shorter delay. This was interpreted as indicating that binding is stronger for stimuli presented close in time, while the larger preparation time allows for a more powerful use of contingency knowledge. In both cases, these dissociations suggest that binding and learning effects may result from processes that are (wholly or partly) unrelated.

Alternative interpretations of these results from the perspective of a unitary mechanism view might be possible (see Schmidt, Giesen, et al., 2020, for a discussion), but further work is needed to explore the extent to which learning and binding are or are not due to the same processes and, if they are different, how the two interact with one another (Giesen & Rothermund, 2015; Moeller & Frings, 2017b). For example, Giesen and Rothermund used a distractor-response binding procedure in which stimulus repetitions were: (a) predictive of response repetitions (i.e., a distractor repetition indicated that the target was likely to repeat as well), (b) predictive of response changes (i.e., a distractor repetition indicated that a different response was likely), or (c) non-predictive. They found that binding effects were larger when distractors predicted response repetitions and smaller when distractors predicted response changes. Such results could be considered as a complex form of sequential learning or as the result of learning processes modifying binding processes.

Conclusion

This review (see also, MacLeod, 2019) provided an overview on research using the colour-word contingency learning procedure, as well as those using similar paradigms. This procedure has proven to be a very useful tool for studying contingency learning in an incidental acquisition context in a simple way. Indeed, reflecting simple Pavlovian learning procedures from animal models, the task requires only a simple manipulation of the pairing frequencies between a target (or several) and a distractor stimulus, while avoiding some of the complications of more elaborate procedures (e.g., if participants learn partial or complete sequences in sequence learning; Perruchet & Amorim, 1992; Perruchet et al., 1997; for a review, see Perruchet, 2019; Perruchet & Pacton, 2006; Thiessen et al., 2013). The learning effect observed with the task is quite surprising and robust. The effects observed appear to be primarily due to associations between stimuli and responses (rather than between stimuli), sensitive to the frequencies of item pairings (i.e., the higher the co-occurrence frequency, the faster the responses), and resistant to delays between the start of a predictive stimulus and the eventual target.

Learning in the procedure is extremely fast and adaptive to changes in contingency proportions. This suggests a very fast learning rate, which is also compatible with the powerful influences of recent experiences. Among other things, this led to the interesting idea that learning regularities and more transitive binding effects could be due to the same learning mechanisms (Schmidt et al., 2016). In the habits literature (K. J. Miller, Shenhav, & Ludvig, 2019; Wood, 2017; Wood & Rünger, 2016), the *law of exercise* proposes that learned habits emerge from the simple fact of constantly repeating the same behavior in the same situation (Thorndike, 1911).

This law, like most conceptualizations of learning, focuses on extracting regularities between events (i.e., which events *tend* to go together). Surprisingly adaptive changes to recent events have led Giesen and colleagues (2020) to suggest another law: the *law of recency,* which states that the fact of having performed a behavior in a specific situation increases the probability of performing the same behavior again when the same situation occurs.

In addition to learning speed, the effects observed in the colour-word contingency learning paradigm seem to share other characteristics of automaticity (Bargh, 1994; Moors & De Houwer, 2006). For example, awareness of contingencies does not seem necessary for learning. In addition, awareness does not appear to be strongly correlated with the magnitude of the effect. Learning is also incidental to the main purpose of the task. That is, the participants do not have an explicit goal to learn the word-colour correspondences, but they do anyway. Learning thus seems to be, to a large extent, implicit in nature, although the procedure can be easily adapted to the study of deliberate learning with a simple change of instructions. Explicit and instructed knowledge of the contingencies or the goal to intentionally learn does influence learning. Together, the results seem consistent with Bargh's "four horsemen of automaticity" (1994) : unconscious, involuntary, efficient, and controllable.

We conceptualized the results of the task in terms of exemplar (or instance or episodic) memory: each new event is encoded as a new memory trace (see also, Hintzman, 1984, 1986, 1988; Nosofsky, 1988a, 1988b; Nosofsky & Palmeri, 1997; Nosofsky, Little, Donkin, & Fific, 2011; Medin & Schaffer, 1978; Logan, 1988). In this conceptualization, participants do not necessarily need to learn the *regularities* of the task, but only the individual trial events. Learning effects emerge from similarity-based retrieval. For example, if the word "move" is most often presented in blue, then most of the memory traces of "move" will be linked to a blue response. The presentation of “move” will therefore lead to a recovery bias in favor of a blue response. This idea was implemented in an artificial neural network learning model that we have widely applied to various research areas: practice, contingency learning, timing, binding, attentional control, task switching, and instructional implementation (e.g., Schmidt, Liefooghe, & De Houwer, 2020; Schmidt et al., 2016). It is difficult to know whether it is even possible to distinguish between theories of learning based on the “strength” of associations and exemplars, because their predictions are often identical (Barsalou, 1990). Indeed, it is quite possible to consider these two views as different conceptual abstractions of the same underlying neural mechanisms.

Some other theories of learning propose that learning is based on *propositional reasoning* (Mitchell, De Houwer, & Lovibond, 2009). This view suggests that concepts do not simply associatively bind automatically. Instead, the concepts are linked together in a structured and relational way. No one disagrees with the idea that such propositional processes contribute to learning, but we generally assume that associative learning, even implicit learning, also contributes to learning (e.g., McLaren, Green, & Mackintosh, 1994). This is reflected in *dual-process models* that assume two systems (e.g., Gawronski & Bodenhausen, 2006; Sloman, 1996; Strack & Deutsch, 2004): one explicit and based on reasoning, the other implicit, automatic, and based on association. This debate has been going on for a long time and it is unlikely that all readers will be convinced, but it seems difficult to reconcile the results of the colour-word contingency learning paradigm with the idea that learning is based exclusively on propositional reasoning.

The procedure is also a useful tool in the analysis of learning phenomena traditionally studied in animals or in explicit human learning, for example, cue competition effects, compound-cue learning (or “occasion setting”), and relearning. The paradigm has proved useful not only to simply reproduce such phenomena in another paradigm, but also to answer questions about the origin of these observations from explicit reasoning or their emergence in incidental learning conditions. For example, we observed cue competition effects, such as blocking and overshadowing, only when learning was intentional. This might suggest that these latter effects are not a simple result of the rules of association, but rather of decisions made about the regularities learned (e.g., “Yes, Stimulus X is often paired with the outcome, but this may be due to the presence of Stimulus A”). This may seem incompatible with several popular explanations of cue competition effects. For example, the Rescorla-Wagner model (Rescorla & Wagner, 1972) suggests that in a blocking phase, associations do not form (as strongly) between Stimulus X and the outcome due to pre-existing associations between Stimulus A and the outcome. Similarly, other theories suggest that participants reduce their attention to Stimulus X (e.g., Mackintosh, 1975). Our results suggest that learning occurs automatically, but the influence of this learning on behavior depends on reasoning about the meaning of the associations. This is consistent with, for example, retrieval-based theories (e.g., Kaufman & Bolles, 1981; Matzel, Schachtman, & Miller, 1985). There is an ongoing discussion about the conditions under which cue competition effects occur. For example, overshadowing is reduced with prolonged training (S. Stout, Arcediano, Escobar, & Miller, 2003), a longer presentation of the cues (Urushmara & Miller, 2007), short trial spacing (S. C. Stout, Chang, & Miller, 2003), and weaker contingency manipulations (Urcelay & Miller, 2006). There has also been a recent debate on the conditions under which blocking occurs (Maes et al., 2016, 2018; Soto, 2018), with many studies that did not produce the effect.

The procedure also led to new directions in the modeling of human performance and the relationship of regularity learning to other phenomena such as binding effects, categorical learning, and evaluative conditioning. Although not discussed in this review, the procedure has also inspired work illustrating confounds due to contingent regularities when researchers have a different study objective. When stimulus frequencies are unintentionally biased, a learning effect can emerge and be misinterpreted as an effect of another cognitive process, such as attentional control (for reviews, see Schmidt, 2013, 2019; for some solutions, see Braem et al., 2019).

While much has already been done with the colour-word contingency learning paradigm and other variants of this task, much remains to be discovered. For example, a new direction currently being explored in our lab is an extension of the task to a musical learning context (Iorio, Šaban, Poulin-Charronnat, & Schmidt, 2020). For example, beginning musicians learn to read musical notation rather slowly during their musical training (Hubicki & Miles, 1991), but our goal is to explore whether the same type of rapid acquisition observed in our incidental learning procedures can also be generated with a music-scale learning procedure (Grégoire, Perruchet, & Poulin-Charronnat, 2013, 2014a, 2014b, 2015). Many other adaptations could be devised for other experimental and applied situations (e.g., language acquisition), leaving room for many new and exciting directions for research in the future.

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