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Temporal contiguity in associative learning: Interference and decay from an historical perspective.

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Abstract

The greater the separation in time between two events, A followed by B, the less likely they are to become associated. The dominant explanation of this temporal contiguity effect has been trace decay: During the interval between A and B, the trace left by A becomes too weak by the time B occurs for an association to be formed between them. Pavlov adopted this idea in the context of classical conditioning and Hull used it to account for the deleterious effect of delaying reinforcement on the acquisition of instrumental responses. By 1960 various studies supported the conclusion that animals could not learn to associate two events separated by more than around 45 s. Research on human skill acquisition with delayed feedback and later studies using causal or predictive judgment tasks indicated that explicit cognitive processing is generally involved when humans associate events separated by more than a few seconds. The discovery of long-delay taste aversion learning prompted Revusky's (1971) alternative analysis of contiguity effects in terms of interference: The greater the separation between A and B, the more likely that extraneous events compete for association with A and B. Although the analysis of overshadowing provided by associative learning theories provides a context for this account, none of these theories provide a satisfactory account of evidence on temporal contiguity from a wide range of animal studies. Alternative timing theories are arguably also unsatisfactory.

(232 words)

Whether or not we come to associate two distinct events is largely determined by how close together in time they occur. The major importance of temporal contiguity on the formation of associations has been accepted for as long as such learning has been of interest. Despite its importance, there have been few attempts to explain why this factor should be important. The relative lack of interest in contiguity can be seen as an example of the kind of phenomenon described by Chomsky: "One difficulty in the psychological sciences lies in the familiarity of the phenomena with which they deal. A certain intellectual effort is required to see how such phenomena can pose serious problems or call for intricate explanatory theories. One is tempted to take them for granted as necessary or somehow 'natural'" (Chomsky, 1968; p.21).

Over the past 100 years of associationist learning theories a variety of paradigms have been used to examine how learning by animals and by human participants is affected by varying the temporal relationship between two events. Instead of the more usual comprehensive review of such research within a particular paradigm, this review looks at key results obtained across a variety of research procedures to see whether general conclusions concerning temporal contiguity can be reached. It will be seen that a frequently occurring issue is whether the increase in difficulty of learning that A is followed by B, as the time interval between the events increases, is to be explained in terms of a declining memory trace of A or in terms of increasing interference from other events.

There has been considerable recent interest in the neural mechanisms underlying learning about events that are separated in time. Some important studies have indicated that the brain areas involved in such learning are distinct from those involved in learning about contiguous events (see review by Raybuck and Lattal, 2013). These studies and other neurobiological research related to temporal

contiguity are beyond the scope of the present review, which is limited to purely behavioral evidence. In passing, it may be noted that most neurobiological research on this topic has assumed that memory trace decay is the sole process underlying learning impairments produced by increasing temporal separation and that consideration of the role of interference, the central theme of this review, may be productive for future neurobiological research.

Among the particularly influential theories of classical conditioning from the 20th century (e.g. Mackintosh, 1975; McClaren & Mackintosh, 2000; Pearce & Hall, 1980; Pearce, 1987; Rescorla & Wagner, 1972; Wagner & Rescorla, 1972), only Wagner (1981), Wagner and Brandon (2001) and the real-time model of Sutton and Barto (1981) offer any account of temporal contiguity. Disinterest among many major theorists has been accompanied by relatively little experimental attention to temporal contiguity, with the notable recent exception of research related to timing that is considered in the final section of this review. The last review of research on temporal contiguity in classical conditioning was published over 30 years ago (Gormezano & Kehoe, 1981). This concentrated on studies using the nictitating membrane preparation with rabbits. In the section below that considers this type of research, we concentrate on studies subsequent to this review.

One aspect of temporal contiguity is apparent to anyone who has tried to train an animal to behave in a particular way. To persuade a dog, for example, to sit up and beg will prove very difficult if a reward for completing such an act is not given until some minutes later, but very easy if the reward is immediate. Understanding the effects of *delay of reinforcement* was of considerable interest to a previous generation of learning theorists (e.g. Hull, 1943; Spence, 1956; Mowrer, 1960). Perhaps reflecting recent disinterest, the last comprehensive review of research on

delay of reinforcement in instrumental learning was published nearly fifty years ago (Renner, 1964), although supplemented by review of a further decade of research by Tarpy and Sawabini (1974). These reviews were entirely restricted to experiments on delay of reinforcement in instrumental conditioning and, since they provide a detailed account of this literature, the present article is selective in its treatment of pre-1974 research on this topic, highlighting only studies that were particularly important in terms of theoretical ideas. A more recent review was confined to the operant conditioning literature and concentrated on the effects of delaying reinforcement on behavior maintained by various reinforcement schedules (Lattal, 2010). The latter topic is not of concern to the present review. Instead, we examine research directed to questions on how initial learning about a relationship between two events is affected by their separation in time.

One aim of the present review is to provide an account of research on temporal contiguity that spans both instrumental and classical conditioning. A second is to draw attention to the powerful, yet too often ignored, claims of interference theory and to the problems of its alternative, trace theory, that is too often assumed to be true by default.

Philosophical ideas and pioneering experiments on temporal contiguity

Acknowledgement of the importance of contiguity can be found in Aristotle's *De Memoria et Reminiscentia* (c.350 BC), although it was not until the 18th century that the principle was made more articulate and developed by the British Associationist philosophers, notably Hume. Neither Aristotle nor Hume distinguished between spatial and temporal contiguity, but seemed to consider them as two facets of the same principle. Hume (1739/1975) proposed that an apparent causal relationship

between two events separated in time can be observed upon closer examination to consist of a causal chain linking the cause to the effect, such that consecutive elements of the chain are contiguous. A little later Hartley provided in 1749 the first theory of associative learning that appealed to events within the nervous system. To account for associations between events that are somewhat separated in time, Hartley suggested that 'after the object of sensation has been removed, the sensation and its vibrations persist briefly, but become fainter the while' (Boring, 1957; p.197). These 18th century ideas were to dominate the study of learning for much of its history, while the priority placed on contiguity in the formation of associations between psychological states by Hume was readily embraced in the earliest texts on modern psychology. Spencer (1855), for example, stated that: "When any two psychical states occur *in immediate succession*, an effect is produced such that if the first subsequently recurs, there is a certain tendency for the second to follow it" (p. 530, emphasis added).

Despite the widespread recognition of the importance of temporal contiguity in Western philosophy, empirical research on this factor began only when experimental psychology emerged as a scientific discipline towards the end of the 19th century. The first experiments on the role of temporal contiguity in human learning and memory were carried out by Ebbinghaus in Germany (Ebbinghaus, 1885), closely followed by the first experimental studies of this factor in animal learning that were carried out almost simultaneously by Pavlov in Russia and Thorndike in the USA. Between them, the latter two established a tradition of conditioning research that has used animals as subjects. This review concentrates on data and theory concerning temporal contiguity from this tradition. However, it also briefly looks at research that has examined the role of temporal contiguity in human learning.

The two most influential books in early 20th century learning theory, Thorndike's *Animal Intelligence* (1911) and Pavlov's *Conditioned Reflexes* (1927), both mention, albeit briefly, temporal contiguity as an influence on learning. Thorndike (1911) proposed that the rate of learning diminishes as the interval between response and satisfaction/discomfort is increased: "If, for example, four boxes were arranged so that turning a button caused a door to open (and permit a cat to get to freedom and food) in one, five, fifty and five hundred seconds, respectively, the cat would form the habit of a prompt escape from the first box most rapidly and would almost certainly never form that habit in the case of the fourth." (p. 249). Whereas this experiment appears to have been entirely hypothetical, Thorndike did report some empirical data concerning temporal contiguity. However, rather than undertaken as a direct study of this topic, the experiment was intended to provide evidence of images or ideas in animals. A cat had been conditioned to climb up the front of its cage as the experimenter approached with a piece of fish. Once this behavior was established, 10 s prior to approaching the cage the experimenter would clap his hands four times and say: "I must feed those cats". The cat learned to respond to this signal after about thirty trials, leading Thorndike to the tentative conclusion that, since there had been a 10-s interval between the signal and the delivery of food, such learning must be evidence that an 'idea' of the experimenter's approach was triggered by the signal (Thorndike, 1911).

With the benefit of hindsight provided over two decades later by clarification of the difference between instrumental and classical conditioning, it is noteworthy that Thorndike's only empirical examination of learning with a delay, described above, involved a classical, not an instrumental, contingency. A similar contingency was employed by Pavlov (1927), who referred to a special "group of conditioned stimuli"

(p. 39) that terminated prior to the provision of the unconditioned stimulus (US). In such a case, an after-effect, or *trace*, of the conditioned stimulus (CS) remains in the animal's nervous system once the stimulus itself is withdrawn. Reflecting Pavlov's influence, the theoretically-loaded term, *trace conditioning,* has been used ever since to denote a procedure in which CS-offset precedes US-onset and the term, *trace interval,* is generally applied to the interval between these events. However, in the context of instrumental conditioning a procedure that introduces a time interval between the target response and the occurrence of some reinforcing event is termed – as noted above - *delay of reinforcement.*

Experiments on trace conditioning were among the earliest studies of conditioned reflexes carried out in Pavlov's laboratory (Pavlov, 1906; reprinted1928; p.93). The results led to his view, noted above, that a connection is formed, not between a CS and US separated in time, but between the sensory after-effects of the CS and the US. This is in contrast to the view of Thorndike (1911), who expressed skepticism about a direct connection between the "neurosis of [his signal], and with it the psychosis" and "the impulse to [climb up the cage]" (p. 113); meaning in more modern terms, that he doubted whether memory of his four claps could be sustained in sensory memory for the 10-s interval he employed and implied that a more abstract encoding of this signaling event must have entered into association with the response of climbing up the cage.

Trace conditioning experiments carried out in Pavlov's laboratory normally involved CS offset-US onset intervals no longer than a few seconds. However, some experiments used stimuli whose offset occurred up to 3 min before food arrived, yet could still function as effective CSs. After repeated presentations, Pavlov reported that a conditioned salivary response still did not occur during the presence of such a

CS but instead began to appear at a certain time after its offset (the *inhibition of delay* effect). He interpreted this as indicating the involvement of cyclical internal events during the long trace interval that essentially functioned as what later would be called an "internal clock" (Pavlov, 1927; pp.40-43). The characteristic absence of any detail in Pavlov's reports means that we do not know whether such conditioning with long trace intervals was obtained in dogs that had already served in experiments using short or zero trace intervals. This possibility seems very likely, given that normal practice in Pavlov's laboratory was to use a few dogs in experiment after experiment (Boakes, 1984; p.118; Todes, 2002). As noted below, prior experience can be an important factor in whether an animal displays conditioned behavior as a result of a conditioning procedure involving long trace intervals or delays of reinforcement.

Research on delay of reinforcement in instrumental conditioning and maze learning by rats: 1917-1943.

Watson (1917) was the first researcher to study the effect of delaying delivery of a food reward after a rat had completed an instrumental response. Subsequent studies of delayed food reward used maze learning rather than acquisition of a singular instrumental response (e.g. Simmons, 1924; Warden & Haas, 1927). These early studies found little effect of delaying the reward. However, they all suffered from the shortcoming that their rats were exposed during the delay interval to stimuli, mainly olfactory or contextual, that would almost certainly have become associated with food. Consequently, these stimuli would have provided immediate conditioned, or secondary, reinforcement of the target response and this would explain why these

experiments found little or no effect of varying the delay of reinforcement (see Renner, 1964).

Hamilton (née Haas) (1929) was the first to attempt to remove the direct influence of cues associated with food during the delay period. In two experiments she detained rats in a compartment separate to the food compartment during the delay. Delays of reinforcement of 1 min or more produced a marked increase in the time that rats took to learn a maze. A similar approach was applied to instrumental conditioning by Roberts (1930), who confined his rats to the same chamber in which the instrumental response – contact with a pendulum - was performed. The response resulted in the opening of a door leading to a further chamber ("feeding cage"), in which rats received food. The four groups in Roberts' (1930) experiment differed only in the amount of time that elapsed between pendulum-contact and the opening of the feeding cage door; the delays employed were 0, 5, 10 and 30 s. All four of Roberts' (1930) groups learned to perform the target response reliably, but more trials were required for mastery as the delay increased. This was attributed, at least in part, to the development of competing responses, behavior Roberts referred to as "mislearning", e.g., waiting in front of or attacking the door to the feeding cage. Roberts (1930) appears to be the first publication in which the idea of response competition (a type of interference, but distinct from stimulus interference in Pavlovian conditioning) was invoked as an explanation for the deleterious effects of delay.

The experiments described so far were largely atheoretical. Following Hull (1932) the study of temporal contiguity was dominated for three decades by Hull's ideas, notably by his development of S-R-reinforcement theory in collaboration with colleagues such as Spence. It should be noted that within this theoretical framework

researchers were concerned almost exclusively with the effect of delaying a reinforcer on its ability to strengthen an S-R connection based on the preceding co-occurrence of the stimulus and the response. Following Thorndike and Watson, Hull-Spence theory rejected the possibility that animals, or even humans, formed a direct association between a stimulus or response and a subsequent reinforcing event.

The more theoretical concerns of the 1930s and the avowed aim of discovering a precise quantitative function to summarize the effects of temporal contiguity on learning are first seen in a study reported by Robinson (1932). He raised the question of whether the so-called "law of contiguity" should be considered a quantitative or a qualitative law; that is, can conditioning and contiguity be considered as two continuous variables related by a quantitative function, or does contiguity influence conditioning in an all-or-none fashion? This question was suggested by early research on human paired-associated learning that, as discussed in a later section, distinguished between simultaneous and successive procedures. Robinson (1932) favored the quantitative account on both logical and empirical grounds, citing the results of Yarborough (1921) as evidence.

Hull's interest in such matters arose partly as a reaction to the work of Gestalt psychologists and their attack on behaviorism and partly from his ambition to develop an entirely mechanistic account of even the most complex forms of behavior (Smith, 1986; pp.151-154). More specifically, Hull wished to explain a very simple effect found in maze experiments: When rats are given a choice between a shorter and longer path through a maze, they come to choose the shorter path to the goal box (e.g., DeCamp, 1920).

Hull addressed this problem in an article that started with the claim that "one of the most persistently baffling problems which confronts modern psychologists is the

finding of an adequate explanation of the phenomena of maze learning" (Hull, 1932; p.25). According to his *goal-gradient hypothesis,* rats prefer the shortest route to a goal box because conditioning of component responses in a behavior sequence becomes progressively weaker the more distant a component is from the goal. Thus, as the initial component of the behavior sequence required for the shorter path is less remote from the goal than that for the longer path, this is more strongly reinforced. This analysis reduced effects of spatial separation to those of temporal separation. It provided the basis for the continuing hostility of Hull-Spence theory to the idea that spatial learning involves special processes, as championed by Tolman, the main critic of Hull's approach (e.g. Tolman, 1932).

Support for the goal-gradient hypothesis was soon provided by Anderson (1933), followed by the more interesting experiments reported by Wolfe (1934), who was the first to employ discrimination procedures in this context. In one experiment rats placed in a T-maze were rewarded for turning in a particular direction (either left or right). Immediately after they had chosen a path, they were detained in a delay chamber. A reward following a correct choice was then given after periods of time that ranged from 0 to 20 min. Wolfe found that the performance of rats experiencing delays of up to 5 s was superior to that of rats experiencing longer delays. A second experiment used a black-white discrimination procedure and found that rats given immediate reinforcement or a 30-s delay performed better than rats experiencing 1- and 10-min delays.

The most notable – and subsequently by far the most frequently cited - of the studies that attempted to specify the precise nature of the goal-gradient were those of Perin (1943a; 1943b). These followed the introduction of the Skinner box as an important improvement on previous methods for investigating response-reinforcer

contingencies, together with a sketchy report by Skinner on the effect of delaying reinforcement from 1 to 8 s (Skinner, 1938; pp.73). One of Perin's primary aims was to exclude the influence of secondary reinforcement so that a gradient of primary reinforcement could be accurately determined. Taking the rationale of Roberts (1930) one step further, Perin provided the constant experimental environment of a conditioning chamber in which a protruding lever was withdrawn once an initial lever-press response occurred and there was then a delay before food was delivered. Thus, the "problem box", "delay compartment" and "food box" of earlier studies were now all the same chamber. Perin (1943a) found that latencies to press the lever increased with the delay between a lever-press and food delivery. A steep gradient of reinforcement was obtained, with no evidence of learning in rats given the 30-s condition. A second experiment was designed to employ a measure other than latency, namely accuracy of response differentiation (Perin, 1943b). This employed a procedure similar to that described above, except that the vertical lever could be pushed to left or right, with only one direction reinforced. The direction in which each rat showed a natural preference for pushing the lever during pre-training was used as the *incorrect* response during training and thus the rats' performance in training tended to begin from below chance. Using this procedure, the performance of immediately reinforced rats did not differ markedly from those experiencing a 2-s delay, while performance with longer delays (5, 10 and 20 s) was slower to develop, as was consistent with Perin (1943a).

The results obtained by Wolfe (1934) and Perin (1943a, 1943b) led Hull (1943) to revise his goal-gradient hypothesis. An important modification to the original hypothesis was the distinction between two types of gradient: A primary gradient (that Hull called the *gradient of reinforcement*), which is much steeper than the

original, and a *derived* gradient, which is shallower than the primary gradient and determined by secondary reinforcement (essentially the *goal-gradient* described by Hull, 1932). Thus, according to the revised goal-gradient hypothesis, learning with long delays requires at least one source of secondary reinforcement, while the removal of all potential sources of secondary reinforcement (a difficult task, as pointed out by Perin, 1943b) would mean that only short delays (less than about 30 seconds) would support learning.

As for processes that might underlie these gradients of reinforcement, Hull simply concurred with Pavlov's idea of a stimulus trace; he decided that recent research in sensory physiology "tend to substantiate the *stimulus-trace hypothesis* of Pavlov" (Hull, 1943; p.42). This adoption of Pavlov's ideas on temporal contiguity extended to Hull's previous distinction between short and long trace conditioning, the latter referring to the examples, mentioned above, where dogs in Pavlov's laboratory had displayed a conditioned salivary response to a CS that had terminated some minutes before the arrival of food. Hull now agreed that such examples reflected cycles of internal events (a kind of physiological clock) and decided that such learning should be termed *cyclic-phase conditioning.* This was not to be confused with true trace conditioning, the latter being limited to trace intervals lasting only a few seconds (Hull, 1943; pp.173-177).

Spence and response competition.

In 1947 Spence questioned the very existence of a primary gradient, suggesting instead that all learning with delayed reinforcement involved immediate secondary reinforcement. Tentative experimental support for this idea was provided by Perkins (1947) followed by more definitive results from Grice (1948).

Grice (1948) employed a black-white discrimination box, in which rats were required to select one of two parallel alleys, one white and the other black, and only one led to food. Using such a task, Grice found a very steep gradient of reinforcement, with three of the five subjects in a 10-s delay condition failing to learn. Furthermore, when secondary reinforcement was explicitly introduced, whether external (e.g., black goal box follows black alley) or internal (obstacles in each alley force rats to perform certain movements following a certain choice of alley), the gradient was extended. Grice concluded that these results supported Spence's (1947) theory that no primary gradient of reinforcement exists, and that all delay learning involves immediate secondary reinforcement.

Spence's subsequent reversal of his ideas about learning with delayed reinforcement were based primarily on a series of studies from his own laboratory. These suggested that long-delay learning is retarded or prevented only by the presence of competing responses. According to this account, a delay between an instrumental response and reinforcement provides the opportunity for other responses to occur during the delay and, the longer the delay, the greater the competition with the target response. By implication, learning with long delays should readily occur if the opportunity to perform other responses during the delay is reduced. In support of this account, Spence (1956) cited a study in which one group of rats learned to press a lever for food when food followed 1 s after a lever-press, then continued to lever-press when the delay was lengthened to 10 s (Harker, 1956). A crucial observation was the tendency of rats in the 10-s delay stage to remain oriented towards the location of the lever and the adjacent food cup during the delay, thus reducing the likelihood of the development of competing responses (Harker, 1956). In a related study rats learned a lever-press response with a 10-s delay if

they were restrained in such a way that they remained oriented to the lever and food cup during the delay (Carlton,1954; cited in Spence, 1956).

It is worth noting that Spence's conclusion from these studies - that instrumental learning under conditions of delayed reinforcement is retarded only by the occurrence of competing responses during the delay – did not mean that he had abandoned the idea that temporal contiguity is important for instrumental conditioning. On the contrary, he announced that "tentatively" he had become a "contiguity theorist" (Spence, 1956; p.151). What this meant was that he was abandoning the basic assumption that he, Hull and almost all other learning theorists within the neo-behaviorist tradition had adopted from Thorndike (1911), namely, that, when in the presence of a stimulus (S) a response (R) is made, a connection between S and R is formed if, and only if, R is followed by some reinforcing event. Instead, he was agreeing with the contiguity theory proposed by Guthrie (1930) that temporal contiguity of S and R is a sufficient condition for an S-R connection to be formed. According to Spence's revised account of instrumental learning, the role of reinforcement is a motivational one. The degree to which an animal expects reinforcement and the size and quality of the expected reinforcer – incentive strength, K, based on fractional anticipatory responses in Spence's theory – affects performance of the instrumental response, R, when S is present.

Perhaps provocatively, Spence (1956) adopted a 2-factor theory that was the diametric opposite to the increasingly influential one proposed by Mowrer (1947). Mowrer, along with Skinner (1938), Konorski and Miller (1937) and other contemporaries had argued that the learning processes underlying classical and instrumental conditioning were quite different, claiming that the consequence of a response was critical in instrumental learning but not in classical conditioning, the

latter depending solely on the CS and US occurring close together in time. Spence
now at last agreed that instrumental and classical conditioning involve different
learning mechanisms but claimed that – as noted above – instrumental learning
depended on contiguity only, whereas reinforcement (the occurrence of a non-neutral
US) was necessary for classical conditioning (Spence, 1956; p.151).

Temporal contiguity in Mowrer's two-factor theory

In suggesting that learning across any delay could be attributed to immediate
secondary reinforcement, Spence's (1947) aim was to solve the problem of retro-
action, the assumption that a reinforcer acts backward over time to strengthen a
stimulus-response (S-R) connection. By proposing that all reinforcement is
immediate, Spence was able to avoid the logical dilemma of an effect (the
strengthening of an S-R connection) preceding its cause (the reinforcing stimulus).
Within an S-R-reinforcement theory effects of delayed reinforcement can be
explained only by the unlikely assumption that a *connection* between an S and an R
can "reverbrate" in the brain and thus be strengthened by delayed reinforcement. On
the other hand, the assumption that the effects of a *stimulus* can reverbrate for some
time seemed as plausible to Mowrer (1960; p.362) as it had to Pavlov. The idea of a
persisting "neural after discharge" provided the basis for Mowrer's analysis of
learning across delay intervals within the framework of his revised two-factor theory.

The experiments from Pavlov and Thorndike onwards that have been described
thus far were based on positive reinforcement, almost always employing food reward
given to hungry animals (but see Yarborough, 1921). In contrast, Mowrer's ideas
were largely influenced by research on punishment and avoidance learning. Two
such studies were particularly important. In one rats were punished for taking food

from a stick inserted into the conditioning chamber by delivery of a shock that could occur after an interval that varied across groups. Such punishment was found to be much less effective if delayed by 10 s, and for delays greater than 30 s it was almost completely ineffective (Davitz, Mason, Mowrer & Viek, 1957). The other influential study used dogs in a shuttle box avoidance task and varied the interval between the warning stimulus – a 2-s buzzer – and the onset of a high intensity shock (Kamin, 1954). The effectiveness of the buzzer in eliciting an avoidance response was tested in extinction. Dogs trained with a short (3 s) trace interval showed very slow extinction, whereas when the trace interval was 17 s or longer the response disappeared very quickly. For Mowrer these studies indicated that both responses, as in Davitz et al. (1957), and stimuli, as in Kamin (1954), could become associated with a shock over a trace interval of up to around 30 s, and as a result both kinds of events could come to evoke fear.

Mowrer (1960; p.367) compared these shock-based studies with a food-based experiment using a classical conditioning procedure whereby a 3-s buzzer was followed by food delivery after an intervening trace interval that varied from 1 to 81 s for different groups of rats. Subsequently, the effectiveness of the buzzer as a secondary reinforcer was tested by mounting a lever in the conditioning chamber and arranging that lever-presses would be immediately followed by the buzzer. The amount of responding supported by the buzzer varied greatly across groups in a way that suggested an effective association between the buzzer and food had been formed only in the groups trained with a trace interval less than 21 s (Jenkins, 1950). For Mowrer these results indicated that Jenkins' rats had associated the emotion of *hope* to the buzzer in a way parallel to conditioning of fear to the stimuli used in the shock-based studies. Furthermore, the temporal gradients appeared to be very

similar in the two kinds of study. Mowrer (1960; p. 375) concluded that "regardless of whether the antecedent event is a response or an environmental stimulus and regardless of whether the ensuing reinforcement is decremental (e.g. food reward) or incremental (e.g. shock), the gradient of reinforcement is negatively accelerated and lasts for upward of 30 to 60 seconds as a limit". Moreover, "further analysis suggests that this common finding derives from the fact that gradients of reinforcement are based on the underlying phenomenon of stimulus trace" (Mowrer, 1960; p.384).

Their learning theorist contemporaries might see large differences between Spence's theory and that of Mowrer – notably, in terms of how classical and instrumental conditioning differed and whether stimuli could come to evoke fractional anticipatory responses as opposed to emotional responses – but they would agree with both that for two events to become "linked", "associated" or "connected" the necessary and sufficient condition was that the events were separated in time by no more than Mowrer's "three quarters of a minute" and possibly even less (Kimble, 1961). A series of studies in the 1960s showed that this belief was entirely wrong. However, before examining these developments, we first turn to research on human learning that was strongly influenced by animal-based research of the Hull-Spence era.

Human skill acquisition and delayed knowledge of results (KR).

Experiments concerned with the effect of temporal separation on human associative learning initially followed Ebbinghaus's (1885) pioneering studies of memory for verbal material. Early experiments found that in general humans learn associations between items more effectively if items are presented simultaneously rather than successively (Bergstrom, 1907; Bigham, 1894). In Froeberg's (1918)

experiment participants were asked to associate two nonsense syllables presented successively, with varying intervals separating each pair. Only under conditions in which participants had to read out numbers during the intervals did performance decline as the interval increased. This appears to be the earliest direct evidence that interpolated activities can interfere with acquisition of a target association.

The subsequent development of research on paired-associate learning and memory is beyond the scope of the present review. Instead we turn to studies involving human participants that are more closely related to research on conditioning using non-human animals.

It was not until the time of Hull's early theorizing about delay that Wolfle (1932) conducted what appears to be the first study of contiguity in human conditioning. In this experiment participants were given an electric shock to the finger, which was signalled by an auditory stimulus. The CR measured was finger withdrawal. Using this procedure, Wolfle (1932) observed little simultaneous or backward conditioning, while conditioning with forward CS-US pairings was possible only with trace intervals of up to 0.6 s.

Most subsequent studies of contiguity in human learning adopted instrumental conditioning with delay of reinforcement as their initial animal model. These human equivalents used *knowledge of results* (KR, later to be labelled *information feedback*) as the primary reinforcer. The first study of this kind was that of Lorge and Thorndike (1935), in which participants were trained to throw a ball over their head at an unseen target. In this within-subjects design, feedback on performance was given either immediately or 1, 2, 4 or 6 s after the response. Also included was a condition in which feedback was lagged, i.e., feedback for a response was provided only after one or more subsequent performances of the response, in an attempt to compare the

efficacy of an "empty" delay interval with a "filled" one. The results suggested that feedback was equally effective in all of these conditions, leading Lorge and Thorndike (1935) to suggest that, if the response can be "kept in mind" until feedback is given, then feedback is effectively immediate.

   Subsequent studies of KR delay provided results more consistent with findings with non-human animals; namely, that long delays generally result in poorer learning (Angell, 1949; Bilodeau,1956; Bourne, 1957; Lipsitt & Castenada, 1958; Lipsitt, Castenada & Kemble, 1959; Saltzman, 1951; Wolfle, 1951). On the other hand, several failed to obtain such an effect (e.g. Bilodeau & Bilodeau,1958; Noble & Allcock,1958). These mixed results and the frequent discrepancies between human and non-human animal experiments on delay of reinforcement led Brackbill and Kappy (1962) to propose that humans can bridge long delays by making use of "response-produced cues". In their own study children were required to discriminate between visual stimuli that could be readily named. Brackbill and Kappy (1962) speculated that the name of the correct stimulus was covertly (and in some cases, overtly) rehearsed during the delay, resulting in delayed KR being as effective as immediate KR. They also made the important observation that, when participants were tested a day later, the performance of those that had received delayed feedback was superior to those whose feedback had been immediate, concluding that the greater opportunity to utilize response-produced cues in the delay conditions resulted in an effect analogous to increased resistance to extinction. Subsequent, but unrelated, research involving rats demonstrated greater resistance to extinction following training with delayed reinforcement than with immediate reinforcement (Mackintosh, 1974; pp.431-433; Tarpy & Sawabini, 1974).

From a practical point of view, the distinction between "learning" and "retention" is of great importance, since relatively permanent effects of training are of more interest than transient ones for the type of skills used in KR research. Further support for the claim that delaying KR improves retention was provided by the finding that "learning" of French words was just as effective when feedback was delayed by 10 s than when it was immediate, whereas "retention" was superior for the delay condition (Brackbill, Wagner & Wilson, 1964). Similar results were obtained in factual knowledge tasks (Kulvahy & Anderson, 1972; Sassenrath & Yonge, 1968), a verbal learning task (More, 1969) and computer-based multiple-choice knowledge tests (e.g. Sturges, 1978). These studies highlighted the practical importance of the delay-retention effect in an educational setting.

In a comprehensive review of KR in the learning of motor skills, Salmoni, Schmidt and Walter (1984) proposed that any detrimental effects of KR delay might result from the presence of interpolated events. According to this account, empty delays or delays containing simple activities provide no interference, and may actually improve learning and retention, while complex interpolated activities tend to provide interference. Furthermore, Schmidt (1991) revived Brackbill and Kappy's (1962) idea that immediate KR prevents the use of response-produced cues, a particularly relevant factor in motor learning, since proprioceptive, visual and even auditory stimuli can provide useful feedback. Thus, as in animal studies, events occurring during KR delay in human skill learning are a crucial determinant of learning and performance.

The deleterious influence of interpolated events on human learning is consistent with concurrent interference theory (Revusky, 1971), while facilitation of learning by

such events is reminiscent of the marking hypothesis (Lieberman, McIntosh & Thomas, 1979). These developments are described in the section that follows.

Taste aversion learning, stimulus selection and Revusky's concurrent interference theory.

In 1955 Garcia, Kimmeldorf and Koelling reported that rats could acquire an aversion to a flavor after this had been followed 12 hours later by toxicosis caused by X-irradiation. The authors had great difficulty in getting their report published. The procedure was so different from familiar ones in the study of learning that it did not arouse much interest; for example, it is not cited in Kimble's (1961) influential handbook on conditioning and learning. Moreover, experts who did take an interest viewed the results with considerable skepticism (Revusky, 1977a). Reputedly, one editor of a journal to which the report had been submitted decided that finding learning with a delay of such length was "as unlikely as finding bird shit in a cuckoo clock" (Seligman & Hager, 1972; p.15). Nevertheless, subsequent reports of experiments that included more adequate control conditions made it clear that taste aversion learning over a delay was a robust effect (e.g. Garcia, Erwin & Koelling, 1966; Revusky, 1968; Smith & Roll, 1967).

The criticism that toxicosis-based delay learning might be due to some persistent kind of stimulus after-effect, e.g. a lingering or regurgitated taste (e.g. Bitterman, 1975) was ruled out by, for example, the demonstration that an aversion could be established to a high or low temperature of a drink if followed by delayed sickness, even though the fluid must have reverted to body temperature within a short time after being ingested (Nachman, 1970; see also Garcia, Hankins & Rusiniak, 1976). Furthermore, the possibility that long delay learning was entirely limited to

conditioned taste aversions was ruled out by a finding in the context of research on the effects of partial reinforcement on runway performance. Capaldi (1967) found that rats given a single trial in a runway each day but food reward only every other day could learn to associate the outcome of the previous day with the opposite outcome from running down the runway the next day.[1]

Three important studies in the late 1960s laid the groundwork for the associative learning theories that dominated research in animal learning for four decades. Between them these studies demonstrated that temporal contiguity between two events was *not* a sufficient condition for them to become associated. As detailed in many textbooks (e.g. Bouton, 2007), the blocking effect reported by Kamin (1968, 1969), the contingency experiments of Rescorla (1966, 1968) and the relative validity experiments of Wagner, Logan, Haberlandt and Price (1968) made it clear that the conditioned stimuli (CSs) used in classical conditioning procedures can compete for association with an unconditioned stimulus (US) and that stimulus, A, that is a better predictor of the US than B is will be more strongly associated with the US – even if both precede the US by an equal and brief amount of time; if A is perfect predictor and B has no predictive power whatsoever, then the animal in such an experiment may not show any indication of having associated B with the US. This apparent failure to associate B with a contiguous outcome was found even when the outcome was a shock, as in Kamin (1968) and Rescorla (1966; 1968).

The above studies, together with the development and subsequent influence of the formal model that they inspired (Rescorla & Wagner, 1972), had a number of implications for research on the present topic. First, it made very explicit that the goal of a learning theory was to understand learning – conceived as variations in the strength with which two events become associated – and not the much more

ambitious goal embraced by their behaviorist predecessors, that of developing a comprehensive theory of *behavior.* This assumption was accompanied by rejection of the belief in the S-R connection as the fundamental unit of learning that had been seldom questioned by any influential animal learning theorist – other than Tolman (1932) - since Thorndike first put forward an explanation in terms of S-R connections for the results from his pioneering experiments on instrumental conditioning (Thorndike, 1898). Consequently, the search for *the* temporal gradient was now seen as a mistake. How sensitive a conditioned response might be to a trace interval was now recognized to be a function of the response system used to measure changes in behavior. This could range from highly sensitive to intervals more than a second or two, as found in eye-blink conditioning – and as previously favored by Spence – to moderately sensitive, stretching out to even a minute, as in the case of fear conditioning – as previously favored by Mowrer – to very insensitive, as in the case of taste aversion learning (Mackintosh, 1974; p. 63-66).

A second implication for research on temporal contiguity followed from the new emphasis on the importance of the *contingent* relationship between two events and from the absence of any reference to time in Rescorla-Wagner theory or in competing theories that stressed attentional mechanisms (e.g. Sutherland & Mackintosh, 1971; Mackintosh, 1975). These factors combined to diminish interest in the temporal relationship between events in research on learning. This was in contrast to research in the operant conditioning tradition, where the rate at which reinforcement occurred was viewed as the major factor determining steady-state operant behavior (e.g. Herrnstein, 1970). However, this research emphasized *molar* correlations between response rates and reinforcement rates and tended to dismiss the idea that temporal contiguity between response and reinforcement was an

important factor in steady-state operant behavior (e.g. Baum, 1973; Rachlin, 1970; but see Williams, 1976).

A third implication was methodological. For over six decades the vast majority of experiments on animal learning in the English-speaking world had been based on procedures requiring an animal to learn to navigate a maze, run down a straight runway, press a lever or move to one side of a shuttle box before some positive consequence occurred. It was in this context that questions concerning delay of reinforcement had dominated research on temporal contiguity, as described in the preceding sections. Research on temporal relationships using classical conditioning procedures within the American behaviorist tradition mostly used an eye-blink procedure and yielded results of the kind that had led Spence to conclude that traces of more than 10 or so seconds would not support learning (Kimble, 1947; see also Kimble, 1971). The increasing number of studies from the mid 1960s onwards using classical procedures, but with shock as the US and conditioned suppression as the response measure (e.g. Kamin, 1965), found that much longer traces could support fairly rapid learning (Mackintosh, 1974; p.159).

It was in this context of ideas on association between events, rather than reinforcement of responses, and on competition between stimuli for associative strength that Revusky (1971) proposed the first general theory of temporal contiguity to accommodate learning over long delays. A key element in this theory is the concept of *relevance.* This stems from the cue-to-consequence effect, first reported by Garcia and Koelling (1966) and later confirmed by Domjan and Wilson (1972), whereby gustatory cues are more readily associated with illness than visual or auditory cues, whereas the latter are more readily associable with electric shock than are gustatory cues. Thus, in a hypothetical example of concurrent interference, in

which a noise served as the initial event (E-pre in Revusky's terminology) and a
shock served as the subsequent event (E-post in Revusky's terminology), a group
given vinegar to drink during the noise-shock trace interval would still acquire fear of
the noise, whereas a group given a light during the interval would show far less fear
of the noise on a later test. In this case the vinegar was irrelevant to the shock (E-
post), but the light was relevant to this event and thus produced strong concurrent
interference with the noise.

The first basic assumption in Revusky's (1971) account is that the extent to which
an event – E-pre – can become associated with a later event, E-post, depends only
on *concurrent interference* - meaning competition from other events for association
with E-post - and not on the length of time separating E-pre and E-post. The second
assumption is that the degree to which other events can produce interference
depends on both their intrinsic properties or salience – for example, other things
being equal a loud sound will produce more interference than a soft sound – and
their *relevance* to E-post. A third assumption is that interference can arise from
events preceding E-pre or following E-post but, because of what Revusky (1971)
termed the *proximity corollary*, such interference is less effective than that arising
from events occurring within the E-pre to E-post interval.

The application to long delay taste aversion learning is best illustrated by a partial
account of one of the experiments Revusky reported in the chapter in which he first
described his theory (Revusky, 1971). This used a serial overshadowing design. On
Day 1 two groups of rats were first given a small amount of a novel sweet solution of
saccharin to drink and 15 min later they were given a second drink: For the Control
group this was unflavored water; for the Interference group this was a 4.5% vinegar
solution. One hour following this second drink both groups were injected with a

strong dose of lithium chloride. Three days later their preference for saccharin was tested. This test showed strong avoidance of saccharin in the Control group but weaker avoidance in the Interference group. In Revusky's terminology, E-pre was the saccharin and E-post the sickness produced by lithium, while the vinegar provided the source of concurrent interference. The effectiveness of vinegar in interfering with acquisition of the aversion to saccharin resulted from two factors: First, it occurred during the E-pre to E-post interval and, second, tasting vinegar was *relevant* to the subsequent sickness, whereas other events occurring in this interval – such as sounds and visual events – were not relevant, i.e. had low associability with sickness.

The theory was summarized by Revusky (1971) in terms of four conditions that must obtain in order for long-delay learning to occur:

(1)   E-pre and E-post must be highly associable with each other (i.e. E-pre must be *relevant* to E-post);

(2)   an event that precedes E-post (and thus competes with E-pre) must have low associability with E-post;

(3)   an event that follows E-pre (and thus competes with E-post) must have low associability with E-pre; and

(4)   any intervening events must be highly associable with each other.

This fourth condition contains the assumption that, if - for example – a visual and an auditory event occurring during the delay interval between a taste and sickness become associated with each other, their intrinsically low associability with sickness will be reduced yet further.

As clarified later, Revusky rejected as "an overimaginative cognitive theory" the kind of idea suggested by Kamin (1969) that, when some surprising and potentially

important event (an 'E-post') occurs, "the animal scans backward in time in reverse chronological order…. (as if it) has a motion picture camera in its head and runs the film backwards". Instead, he supposed that when an E-post occurs, "all potential E-pres simultaneously compete to become associated with it" (Revusky, 1977b; pp.330-331). How effectively they compete depends on their relevance to E-post, their salience, their relative novelty and their already established associations with other events. But the consequence of adopting this view instead of the 'backward movie' concept was that Revusky had no explanation for why more recent E-pres would compete more effectively than older events. Reluctantly, he conceded that time alone might have some, albeit weak, effect in reducing the associability of an E-pre, but added that this might be amplified by the formation during the delay period of associations between a potential E-pre and some events other than the 'target' E-post (Revusky, 1977b; p.331). We return to this issue later.

It may be noted that Revusky's theory bears close resemblance to theories of forgetting developed in the context of research on human memory. The first prominent theory of this kind by McGeoch (1932) was based on results from paired-associate memory studies, as was an important successor (Underwood, 1957). Later the same general claim – that all forgetting can be explained in terms of interference – was made in the context of short-term memory studies (Keppel & Underwood, 1962; Waugh & Norman, 1965) and was then opposed by research appearing to show that short-term forgetting is based on decay processes (e.g. Baddeley & Scott, 1971). Interestingly, this debate has recently flared up once again. A more formalized equivalent of Revusky's hybrid interference-plus-some decay account has recently been proposed as a theory of human short-term forgetting by Altmann and Gray (2008), while Lewandowsky, Oberauer and Brown (2009) have

argued that there is no evidence for temporal decay in verbal short-term memory and that all forgetting is produced by various kinds of interference.

Revusky's theory (1971; 1977b) is based on interference between discrete events and does not entertain the possibility that *context* associations might provide an important source of interference. Evidence demonstrating the role of context in trace conditioning was first obtained by Odling-Smee (1975). His trace conditioning procedure was carried out in a distinctive black chamber where different groups of rats were given tone-shock pairings under conditions that varied the trace interval between tone and shock from 0 to 90 sec. In a subsequent test the rats were given the opportunity to enter the (now silent) chamber. The test results showed a monotonic function relating trace interval during conditioning and time spent in the chamber: Rats trained with longer trace intervals spent less time in the chamber, indicating that they had learned to fear this context more when they feared the tone less.

Concurrent interference theory resembles the competing response account of instrumental conditioning proposed by Spence (1956), in that the behavioral effect of separating a pair of events depends on what other events are also occurring. Revusky himself conceded that in many cases data cannot distinguish between the two accounts. However, Spence's (1956) account is bound to the S-R tradition and is therefore restricted in scope, whereas Revusky's (1971) theory is set within an associative framework – he later accepted that his interference effects were best seen as examples of serial overshadowing (Revusky, 1977b) - and was explicitly intended as a general theory that can be applied to both stimulus-stimulus and response-reinforcer learning.

Only a few studies have followed Revusky in examining serial overshadowing in long delay taste aversion learning. These have concentrated on two questions. One was whether firmer evidence for proactive interference (produced by events preceding the target taste)[2] could be obtained than that reported by Revusky (1971). Kwok, Livesey & Boakes (2012) found strong evidence for proactive interference (PI) but only after two conditioning trials, thus suggesting a blocking-type process of overshadowing as described by Rescorla-Wagner theory (1972), whereas in the same experiments retroactive interference (RI) (produced by events within target-US interval) occurred within a single conditioning trial (cf. Bond, 1983). The second question was what processes can produce RI within a single trial. This led to experiments that varied the timing of an interfering taste within the interval separating the initial target taste and the delayed lithium injection. The general conclusion resulting from this research is that RI is stronger if the interfering stimulus occurs late rather than early in the delay interval even for 1-trial overshadowing (Cannon, Best, Batson, Rubenstein, & Carrell, 1985: Kaye, Gambini & Mackintosh, 1988; Kwok, Boakes & Harris, under revision). This result is not easily explained by any current theory of associative learning; although Wagner's SOP model (Wagner, 1981; Wagner & Brandon, 1989) – described in a later section – was initially seen by Cannon et al. (1985) to account for their finding, simulation of SOP shows that in fact it predicts the opposite result, i.e. that early presentation of the interfering stimulus should produce greater overshadowing (Kwok, et al., under revision).

Evidence that retroactive interference is more effective than proactive interference bears on the general question of why learning to associate two events becomes increasingly difficult with increased temporal separation between them. As noted above, Revusky (e.g. 1977; p.331) did not see how recency effects could be

explained within his interference theory; thus, if A precedes B and B precedes the US in a conditioning procedure, why should B become more strongly associated with the US than A does? The answer could be that, other things being equal, the interfering effect of A on B (PI) is weaker than the interfering effect of B on A (RI) and thus is only indirectly related to their temporal relationship. However, this raises the question of why RI is more effective than PI (Kwok et al., under revision).

Delay of reinforcement revisited

   To test the generality of his concurrent interference theory, Revusky initiated a series of maze studies with delayed reward that were continued by Lett (1973; 1974; 1975). The idea behind these studies was that the steep temporal gradient typically found in maze experiments (as discussed in the early part of this review) was due to interfering events during the delay period whose influence could be reduced if the rat was removed from the maze. Revusky (1977b) introduced the label, *situational relevance,* for the assumption that events occurring in the same context as E-pre and E-post produce more interference than those occurring in a different context. It may be noted that, if he had adopted the approach taken by Odling-Smee (1975) and accepted that contexts could enter into associations in the same way as discrete events, he could have based this assumption on his previous Principle 4; namely, that that interference with the target association is reduced to the extent that the potentially interfering event is already associated with other events.

   In one example of these maze experiments Lett (1973) gave delayed rewards to rats for making a correct turn in a T-maze. After making a response, whether correct or incorrect, rats were removed from the maze and placed in their home cages for a certain period before being returned to the apparatus, where they received food if the

preceding response had been correct. She found that rats could still learn when response-reward delays were as long as 8 min (see also Lett, 1974; 1975). However, very many trials were needed to obtain evidence of learning when reward was delayed more than a few minutes, there were no control groups to confirm that confinement outside the maze during the delay was indeed critical for long delay learning, and it proved difficult to replicate the results in other laboratories (Roberts, 1976).

One attempt to replicate Lett's (1973) results included a control group of rats that were picked up and then returned to the maze. Surprisingly, this control group learned the position discrimination despite a 1-min delay of reward as rapidly as those confined to their home cage during the delay period (Lieberman, McIntosh & Thomas, 1979; Experiment 1). This result led these researchers to the discovery of an effect known as *response marking*: Discrimination learning with delayed reward can occur more rapidly if a choice response, *whether correct or not*, is followed by a salient event. The latter could consist of the experimenter picking up the rat or - more effectively, it turned out – a light flash or brief burst of noise (Lieberman et al., 1979). The generality of the effect was shown by related experiments with pigeons (Lieberman, Davidson & Thomas, 1985; Lieberman & Thomas, 1986). The explanation they offered was that the memorability – and therefore the associability – of a response was increased if followed by a salient event. Hence, when a minute or two later a food reward was made available, this would trigger a backward search that was more likely to find a marked response than an unmarked response as the likely cause (cf. Kamin, 1969). One result, however, posed a difficulty for their account. This was the finding that presenting a 2-s burst of noise *before* rats made a choice response facilitated learning a left-right discrimination just as effectively as a

burst of noise that followed a response. For this marking effect a different explanation was offered, one in terms of the marking stimulus increasing attention to subsequent responses (Thomas, Lieberman, McIntosh & Donaldson, 1983). Independent of how these marking effects are best explained, what was demonstrated by this series of experiments - together with those reported by Lett - was that, following only minor procedural changes, animals can learn discriminations on the basis of reinforcement delayed far longer than seemed possible to the previous generation of researchers.

Almost as a reprise of the change in methodology from mazes to Skinner boxes that had taken place in the 1930s, theory-driven research on delay of reinforcement following Lett's work almost exclusively used automated instrumental conditioning procedures rather than mazes. By the time of Mackintosh's influential handbook of 1974 evidence had accumulated in support of the idea that responses and stimuli compete for associative strength. The first experiments to explore this idea in order to understand delay of reinforcement appear to be those reported by Williams (1975). He used a discrete-trial instrumental conditioning procedure with pigeons whereby reinforcement of a peck was delayed for 10 s. The novel manipulation was to add a brief stimulus just before the arrival of reinforcement. This produced a marked reduction in pecking compared to control conditions lacking this added stimulus. Williams argued that this reduction was produced by serial overshadowing – or "response blocking" as he referred to the effect – whereby the added stimulus successfully competed with the response for association with reinforcement (see also Williams, 1982). Over two decades later he returned to this problem, inspired by results reported by Lattal and Gleeson (1990).

These researchers adopted the simple approach to the study of delay of reinforcement that Skinner had sketched in 1938. They simply left their untrained animals – pigeons in the first three experiments and rats in the final three – in the conditioning chambers and studied the rate at which the animals acquired the target response when this was followed by reinforcement delivered 10 or 30 s later. Previous experiments of this kind had seemed difficult to interpret because any repetition of the response during the delay period would also be followed – and sometimes very closely - by reinforcement. Consequently, such adventitiously reinforced responses might produce the misleading conclusion that response acquisition had occurred despite some considerable programmed delay of reinforcement. The novel feature introduced by Lattal and Gleeson (1990) was an omission or "resetting delay" contingency whereby if, for example, an animal in a 10-s delay condition followed the to-be-reinforced response with a second response before the 10 s had elapsed, then the clock was reset so that a 10-s response-free period had to occur before reinforcement was delivered. Despite this omission contingency, their animals acquired the instrumental response, even when this was to push against a lever suspended from the ceiling at some distance from a rat's food hopper and with a 30-s delay of reinforcement (Lattal & Gleeson, 1990; Experiment 6). It should be noted, however, that at least 3 or 4 long sessions were needed before the animals responded consistently at more than a modest rate of 1 response per min.

When Williams (1999) returned to this topic, his rats were given a 30-s delay of reinforcement for lever-pressing under free operant conditions. As with his early pigeon experiments, a "blocking" group received a brief stimulus – 5-s illumination of the house-light – immediately prior to food delivery. This group failed to acquire

lever-pressing, whereas the response was acquired by a control group for which the delay-of-reinforcement period was unfilled by any added stimulus. These results thus showed complete overshadowing of the response-reinforcer association by the added house-light stimulus. Williams (1999; Experiment 1) also included a third group for which the house-light stimulus immediately followed each response. This group showed rapid acquisition of lever-pressing, thus replicating the response marking effect discovered by Lieberman, McIntosh & Thomas (1979) and demonstrating that the effect of an added stimulus critically depends on where it occurs in the delay interval.

Meanwhile, evidence had accumulated in support of the proposal that at least part of the decrement in response acquisition produced by delaying reinforcement was due to competition from context conditioning. Dickinson, Watt and Griffiths (1992) used an unusual operant schedule of delayed reinforcement that was designed to ensure comparable rates of reinforcement across different delay values. Under these conditions their rats normally acquired lever-pressing with a 32-s delay of reinforcement but not with a delay of 64 sec. However, if before the start of each daily session rats in the latter condition spent 30 min in the conditioning chamber with the levers retracted, they did acquire the response once the levers were inserted; this suggested that prior exposure to the conditioning chamber weakened competition from context-reinforcer associations (Dickinson et al, 1992; Experiment 3; Dickinson, Watt & Varga, 1996).

In summary, in contrast to comparable studies undertaken early in the 20th century, these late 20th century studies of delayed reinforcement in instrumental conditioning demonstrated that animals can learn to associate actions with their

much delayed consequences to the extent that competition from other events, including the context, is minimized.

Eye-blink conditioning and Wagner's SOP theories

In the context of conditioning research using the rabbit's nictitating membrane response as the conditioned response – or 'eye-blink conditioning' as it will be referred to here - Kehoe, Cool and Gormezano (1991; p.285) noted: "ISI (inter-stimulus-interval)-CR frequency functions have traditionally provided the defining operations for the time course of a hypothetical, sensory-like representation of the CS by which an organism bridges the time gap to the US". Eye-blink conditioning can be unusually sensitive to temporal parameters. Under the conditions in which the majority of such experiments have been carried out, the development of this CR occurs only under a narrow range of inter-stimulus intervals; e.g. an ISI of at least 100 msec and maximum responding with an ISI of 200 msec (Smith, Coleman & Gormezano,1969) and typically no conditioning at all when the ISI approaches 4 s (Schneiderman & Gormezano, 1964). (As noted earlier, a more detailed treatment of early eye-blink research on this topic may be found in Gormezano and Kehoe, 1981).

Of the various associative learning theories that have been applied to a range of learning phenomena over the past four decades, the one that has relied most extensively on data from eye-blink experiments has been the SOP ('Standard Operating Procedures') theory first proposed by Wagner (1981) and later extended (Wagner & Brandon, 1989; 2001; Brandon, Vogel & Wagner, 2003; Wagner & Vogel, 2010). As noted earlier, most major theories of associative learning from the 1970s and 1980s omitted any reference to the issues of concern in the present review and

ignored time as a factor in conditioning experiments. In contrast, Wagner's series of theories have been explicitly based on the principle of strict temporal contiguity[3].

The first core assumption of SOP and its successors is that representations of stimulus events – or, later, the elements of such representations – can be in three states: Active (A1), Less Active (A2) or Inactive (I). The second assumption is that the transitions from A1 to A2 and from A2 to I take place as a result of a decay process. In the original statement of the theory 'decay' is placed in parentheses and the assumption is made "that the "spontaneous" decay from the A1 to the A2 state, and from the A2 to the I state are the result of extra-experimental stimulation that competes for nodal action" (Wagner, 1981; p.11). This assumption was given no further attention in the original statement of the theory and does not seem to have been examined in later developments of the theory. 'Decay' was never again placed in parentheses and instead it is most easily taken to represent a spontaneous process. As for the time course of stimuli in the A1 state, Wagner and Brandon refer to intensity judgments in human psychophysical experiments. These have found that for visual stimuli an initial integration phase of around 0.5s is followed by gradual decline in perceived intensity, whereas for taste stimuli the integration phase takes 3-6s (Marks, 1974). Wagner and Brandon (2001; pp.42-45) suggest that these are the mean times that a stimulus element remains in an A1 state.

SOP is a strict contiguity theory since it proposes that an excitatory link between stimuli is formed only to the extent that representations of the stimuli are simultaneously in an A1 state and that an inhibitory link between two stimuli is formed only to the extent that one stimulus is in its A1 state and at the same time the other is in its A2 state. Almost all the data on which various versions of the theory have been based come from experiments using a delay conditioning procedure, that is, one in

which the CS is maintained until the US occurs. Trace conditioning is hardly ever mentioned in the chapters or articles that report the theory and long delay taste aversion learning is never mentioned at all. The obvious reason is that the theory predicts the impossibility of an excitatory link forming between two punctate stimuli that are separated by more than a few seconds, since the representation of the first stimulus (in taste aversion learning) would be in an A2 or even an I state by the time that the second stimulus occurred. Nevertheless, it should be noted that SOP and its predecessor (Wagner, 1976) have been applied to taste aversion learning by assuming that tastes persist in an A1 state far longer than other types of stimuli (e.g. Best & Gemberling, 1977; Westbrook, Smith & Charnock, 1985).

A key finding for the 'Affective Extension' of the SOP theory (AESOP: Wagner & Brandon, 1989; p.166) was that the optimal inter-stimulus interval in experiments that pair a CS with the delivery of a paraorbital shock to a rabbit depends on what response is measured, as first reported by Vandercar and Schneiderman (1967; see also Schneiderman, 1972). For example, when Vandercar and Schneiderman measured eye-blinks, the optimal interval was 0.75 s; when they measured heart rate as the conditioned response, the optimal interval was 2.25 s. In view of such "divergence of response measures" Wagner and Brandon (1989) followed a number of earlier proposals that a distinction needs to be made between "sensory" conditioning and "emotive" conditioning (e.g. Konorski, 1967). The 'Affective Extension' that turns SOP into AESOP is the proposal that the two kinds of conditioning occur in parallel, following the same basic process, the only difference being that the decay times from A1 to A2 and from A2 to I are much slower for the emotive US representation than for the sensory US representation. In terms of

everyday experience one might describe the sharp pain of a shock as an experience that quickly fades, while the emotional turmoil it triggers is more long lasting.

Despite the above extension, AESOP fails to provide an explanation for one of the key findings that stimulated its development. Thus, to account for the optimum inter-stimulus interval for delay conditioning being much longer for emotive than for sensory conditioning (e.g. Schneiderman, 1972) AESOP would have also to assume that the representation of a stimulus involved in emotive conditioning is distinct – in that it has much longer decay times – from the representation of the same stimulus that becomes involved in sensory conditioning. Given the variation of optimal inter-stimulus intervals across different conditioning procedures, such a proposal leads to the absurd conclusion that there are as many distinct representations of a stimulus as there are ways of measuring a response. The analysis of backward conditioning in terms of AESOP makes it very clear that only a single decay function is assumed for stimuli that have no intrinsic emotive value, i.e. are essentially neutral CSs (e.g. Wagner & Brandon, 1989; Figure 6.9, p.172) and thus variation in optimal timing with "divergence of response measures" is left unexplained.

SOP and its successors also fail to explain a number of other findings concerning the effects of varying the ISI in rabbit eye-lid conditioning. One such finding was discovered in research on "serial-order eye-lid conditioning". In the previous two sections we have described experiments that employed procedures involving a sequence of events, E->Int->Rft, whereby a target event, E – a taste or a response – is followed after some interval by a reinforcing event, Rft – a lithium injection or food for a hungry animal - and a potentially interfering event (Int) is presented at some point during the E-Rft interval. As already noted, these experiments were ones in which the occurrence of Int competed with the E-Rft association. What we have yet

to note is that such procedures are ones in which Int may possibly acquire secondary reinforcing properties and thus may have the potential to increase, rather than interfere with, conditioning of E. Such an effect was detected by Williams (1982) in his series of experiments on response blocking in pigeons.

A much larger second-order conditioning effect has been found when a sequence of two stimuli is used in eye-blink conditioning. The results from such experiments no longer suggest rapid trace decay. For example, Kehoe, Gibbs, Garcia and Gormezano (1979; Experiment 4) arranged that on each trial a 400-msec tone (CS1) was followed either 4, 8 or 18 s later by a 400-msec flashing light (CS2), whose onset was followed 350 msec later by a shock. The CR to CS1 developed rapidly in all three conditions, although later declining somewhat in the 8- and 18-s conditions.

Experiments manipulating a much simpler factor than second-order conditioning have identified a further problem with the assumption that the typical ISI function found in eye-blink conditioning research provides a direct measure of stimulus trace decay. Almost all of the studies described earlier in this section, including those that have provided the main empirical basis for SOP, used massed procedures that involved from 20 - 100 trials per session and relatively short inter-trial intervals, for example, in the range 15 – 300 s. In a series of studies using a delay conditioning procedure Levinthal and his colleagues showed that, if they gave only 1 trial per session, a very different ISI function was obtained (e.g. Levinthal, Tartell, Margolin & Fishman, 1985). In one experiment rates of acquisition of the eye-blink were just as fast with an ISI of 1100 msec as with one of 200 msec; in a follow up, acquisition was as fast with an ISI of 2200 msec as with one of 1200 msec (Levinthal, et al., 1985). They noted that such results indicate that "the role of the ISI parameter cannot be considered in absolute terms". (Effects of manipulating trial spacing have been more

extensively examined using the pigeon autoshaping procedure, e.g. Gibbon &
Balsam (1981), as discussed in the 'Temporal coding' section below.) As for an
explanation of why very long intervals between trials allowed their rabbits to show
eye-lid conditioning at ISIs that do not support conditioning under standard
conditions, they suggest that massing of trials decreases the orienting response to
the CS. This could be translated into the terminology of associative learning theory
as claiming that a long interval between trials ensures that the occurrence of both the
CS and US remain relatively surprising events and this promotes a greater increment
in associative strength than under massed trial conditions.

When varying the inter-trial interval in trace eye-blink conditioning was
subsequently examined by Kehoe, et al. (1991), they confirmed that, whereas under
'standard' conditions of a mean inter-trial interval of 60 s, training with an ISI of 3.2 s
produced very little conditioning, when only one trial per session was given the same
training produced almost as much responding as when an 800-msec ISI was used.
To explain this finding, the authors hint at a different explanation from that offered by
Levinthal, et al. (1985): They appeal to the distinction between learning and
performance, suggesting that massed training may 'detune' the performance
mechanism so that the weak CS-US associations formed with long ISIs fail to
generate eye-blinks. The learning-performance distinction is also needed to make
sense of a more recent finding that, following an initial phase using a long ISI that
failed to produce any conditioned behaviour, in a subsequent phase using a short ISI
CRs occur at both the time of the short and the long delayed US (Ohyama & Mauk,
2001).

We need now to summarize the main points in this section. The main findings from
eye-blink research that influenced ideas about temporal contiguity were that inserting

even a short blank interval between the stimuli – the trace conditioning procedure – produced much weaker conditioning and that, when a delay procedure was used, the optimum procedure for obtaining a high rate of conditioned responding was to arrange that the interval between the onset of the CS and the onset of the US (ISI) was of the order 200-450 msec. Such findings have influenced the development of Wagner's (SOP) model, the first consistent attempt to elaborate in precise detail the basic idea that the CS produces a representation whose intensity decreases with time and that for conditioning to take place the US needs to occur before this stimulus trace has completely disappeared, or changed its state.

The limitations of this approach include the failure to explain the acquisition of associations between stimuli separated by more than a few seconds, as demonstrated by the many examples discussed in previous sections of this article, with taste aversion learning providing the most extreme example. Also, the functions obtained under standard conditions indicating the optimal ISI to be less than 0.5 s turned out to be very different when heart rate was measured. Furthermore, even when the measured conditioned response is the eye-blink, the simple manipulation of changing from massed to spaced trials allowed the development of a high level of responding even for inter-trial intervals of several seconds. We return to the important topic of inter-trial interval duration in the penultimate section where temporal coding theories are discussed.

Temporal contiguity in human associative learning studies

Hume's (1739/1975) views on causality inspired an alternative approach to the study of delay in human learning, one developed in research that examined the attribution of causality. Early research of this sort tended to suggest that the

impression of causality requires strong contiguity, whether participants tested were adults (e.g., Gruber, Frink & Damm, 1957; Michotte, 1963), young children (e.g., Siegler & Liebert, 1974) or even infants as young as 4.5 mos (e.g., Leslie, 1982).

From 1979 onwards a popular method for studying this topic has been based on experiments where participants are exposed to varying contingencies between events - often ones occurring in an imaginary scenario - and are required to make causal or predictive judgments. As reviewed, for example, by Shanks (2007), a dominant approach has been to analyze causal judgments from an associative learning perspective, while an alternative has been to examine cognitive processes involved in such judgments. Only the very few studies within either approach that have been concerned with *temporal* relationships between events are examined in this section.

An early example using an instrumental procedure was loosely based on animal studies of delay of reinforcement in instrumental conditioning. Participants in Wasserman and Neunaber's (1986) experiment were required to illuminate a white light by tapping a telegraph key. Using a design that equated contingency across conditions, they found that higher causal ratings were assigned to response-outcome pairings that were closer together in time. Shanks, Pearson and Dickinson (1989) used a similar method and found that delays as short as 2 s resulted in reduced accuracy in ratings of the response-outcome contingencies. In an important follow-up Shanks and Dickinson (1991) demonstrated that introducing delays between response and outcome affected both causal ratings and response rates in a similar way.

Shanks et al. (1989) acknowledged that, when participants are asked to rate the causal efficacy of a putative cause, they could assume that the term "causes" means

"causes immediately". This is particularly likely for the type of task described above, since participants might reasonably expect a system with an electronic mechanism to produce essentially immediate causal relationships. Such assumptions were addressed by Buehner and May (2002, 2003, 2004; see Buehner, 2005 for a summary of these studies and also Allan, Tangen, Wood & Shah, 2003). These researchers demonstrated that the type of task employed and the instructions given determine whether a response-outcome delay reduces the accuracy of causal rating. For example, when participants were required to rate the efficacy of pressing a button to illuminate a light globe, where illumination followed a button-press by 4 s, ratings were more accurate if participants were first informed that the globe was an energy-saving globe, which took a few seconds to light up, than if this instruction were absent. In a similar series of experiments Hagmayer and Waldmann (2002) demonstrated that, when participants were told about a series of events, their assumptions about the timing of possible cause-effect relationships – for example, whether the effects of eating spoiled oysters normally took either one or two days to emerge - guided their choice of statistical relationships on which to base causal judgments.

Adults served as participants in all the experiments so far cited in this section. In a rare developmental study of this question, Schlottman (1999) examined the role that knowledge plays in children's judgments about causal relationships. In this study children could first examine a device that was otherwise hidden inside a box. The device could be either one that clearly facilitated a near-immediate cause (ball dropping into hole) and effect (bell ringing) relationship or one that could easily be seen to insert a delay of about 3s between the two events (ball rolling down a long and gentle slope). Prior inspection of the device had no effect on the causal

judgements of 5- and 7-year-old children, in that it did not attenuate the deleterious effects of a delay. This result indicated the dominance of contiguity on causal attribution in these younger children. By contrast, the causal judgments made by 9- and 10-year-olds were guided by knowledge of mechanism rather than the effect of delay.

Two studies appear to be the only recent attempts to examine the role of interference in human learning over a delay. Lieberman, Vogel and Nisbet (2008) used an instrumental task where the response was to manipulate a computer mouse that during initial training controlled the movements of a cursor around the computer screen. The main task was to move the now invisible cursor from one side of the screen to an unmarked target area on the other side. Feedback as to whether a participant had hit the target was given 4 s after each response. Acquisition was slower in a condition whereby participants were instructed to move the cursor around the screen during the 4-s delay interval than in a condition where they remained still (Lieberman et al., 2008; Experiment 2), thus demonstrating the influence of what Revusky (1971) termed retroactive interference.

Retroactive interference was also demonstrated in a study by the present authors (Costa & Boakes, 2011) that used a modification of a widely used 'Martian' task (Arcediano, Ortega & Matute, 1996) whereby participants tried to prevent a 'Martian invasion' (US) by making an avoidance response (release of the space bar) just before the invasion was about to take place. The Martian invasion was predicted by the presentation of an abstract visual symbol acting as a warning signal (WS) from 2 s to 8 s (delay interval) ahead of the potential invasion. Between 1 and 5 additional symbols ('distractors') could occur at random times both within the WS-US interval and in the inter-trial interval. Speed of acquisition – in terms of both performance and

of ability to identify the CS – was found to be an inverse function of both the delay period and the number of distractors. Strong support for Revusky's theory came from a causal path analysis indicating that number of distractors in the WS-US interval was the primary factor and that the length of the delay period *per se* had little effect on how rapidly participants learned.

All of the human studies described thus far in this section have employed explicit learning tasks. The role of temporal contiguity has also been examined in at least one study in which participants' performance indicated that they had acquired an association between two events without being given any indication that this was an important part of their task (Elsner & Hommel, 2004; Experiment 1). The training stage involved an *action-effect* learning procedure whereby participants had to press one of four keys on a computer keyboard according to the visual cue presented at the start of each trial. Each key press – *action* – was followed by a different tone – the *effect* – either 50ms, 1,000ms or 2,000ms later (between-subjects factor). Participants were "told that the tones were completely irrelevant to the task and should therefore be ignored." Whether they had nevertheless acquired associations between the key presses and their effects was assessed in a test phase. The tones now functioned as discriminative stimuli for responses that were either consistent or inconsistent with those that had produced a given tone in the first stage. A difference in performance between consistent and inconsistent blocks of trials indicated acquisition of key-tone associations in the previous stage. A comparable difference was found in groups given 50-ms or 1,000-ms delays but no difference was found in the group given the 2,000-ms delay.

The proposed explanation for these results was that only when some event follows a response by less than 2 s is an action-event association formed and this is

because "decay of the codes of simple key presses take longer than 1 but shorter than 2 s." (Elsner & Hommel, 2004; p.144). It should be noted, however, that this study used an indirect measure of associative strength, one that relied on such action-event associations being bidirectional in the sense that the event can later come to evoke the action code. It is possible, therefore, that the failure to find evidence for learning with the 2-s interval reflects the insensitivity of this measure.

A consistent finding across these studies is that human causal or predictive judgments are highly sensitive to intervals of no more than a few seconds between the two target events, suggesting that, in the absence of prior knowledge, human participants are insensitive to relationships between events separated by more than 10 or so seconds. This contrasts with the animal learning experiments described in previous sections that have demonstrated learning about events separated by 30 or more seconds. From an interference perspective this apparent difference could reflect the fact that human participants are rarely tested under conditions that attempt to minimize the occurrence of extraneous events, whereas animals are normally tested in sound-attenuated cubicles in which visual stimuli are under complete control of the experimenter. From an alternative cognitive perspective it could be argued that human participants in experiments where events are controlled electronically have good reason to expect that related events are unlikely to be separated by more than a few seconds. Outside such a setting they might well be able to spot a causal connection between events separated by, say, many months; for example, between conception and birth.

Temporal coding

All theoretical accounts of temporal contiguity examined so far in this review have offered accounts of how the temporal relationship between two events affects the degree to which an individual learns an association between these events but all assume that the temporal relationship does not itself enter into what is learned. In this penultimate section we examine claims that the time interval between two events is an integral part of what is learned about them. Most of the evidence supporting these claims comes from two quite different kinds of research. The first body of research described here remains firmly within the associative learning tradition that has provided the main framework for this review. As will be seen, the second comes from a fundamentally different viewpoint.

A remarkable series of experiments carried out in Ralph Miller's laboratory has employed sensory preconditioning (SPC) and second order conditioning (SOC) procedures, using shock as the US and conditioned suppression of licking as the conditioned response (see early experiments reviewed by Savastano and Miller, 1998). A noteworthy example of this research is a recent study by Molet, Miguez, Cham and Miller (2012). Their first experiment used an SPC procedure. For the 'Integration' group, Phase 1 consisted of two sessions, in which a 3-s clicker (S1) was followed 5 s later by a 3-s tone (S2) for six pairings per session, followed by the two sessions of Phase 2, in which a shock was *followed* 5 s later by S2 (i.e. a trace backward conditioning procedure) for four pairings per session. In a subsequent test presentation of S1 suppressed responding by this group, but had no effect in various control groups. This confirmed previous results supporting Miller's 'temporal coding hypothesis' (e.g. Arcediano, Escobar & Miller, 2003) by demonstrating that rats had both encoded the temporal relationship of the events occurring in the first two phases and integrated this information so as to anticipate a shock following S1. Extinction of

S2 prior to testing of S1 greatly attenuated behavioral control by S1; this – and a similar effect found in a second experiment that used second-order conditioning – suggested that temporal integration occurred at the time of testing (Molet et al., 2012). It may be noted that Balsam and Gallistel (2009) - whose theory is discussed next – do not specify whether events are integrated into a temporal map as they occur or at test.

In a previous section where eye-blink research was reviewed, we noted that, when a rabbit is given a series of trials in which some stimulus precedes shock delivery, the result is highly sensitive to the length of the inter-trial intervals. This appears to be true for all conditioning procedures and has been examined most systematically using autoshaping. These experiments typically employ a classical conditioning contingency whereby food is made available at various times to a hungry pigeon and is signaled beforehand by illumination of a response key, the conditioned stimulus (CS). As first discovered by Brown and Jenkins (1968), this procedure can produce sustained pecking at the response key – the conditioned response (CR) - whenever it is illuminated. A large number of experiments have shown that how quickly a pigeon acquires the response and the rate at which it responds depend – among other factors – on two temporal parameters: The average length of the inter-trial interval and the duration of the CS (e.g. Gibbon, Baldock, Locurto, Gold & Terrace, 1977). Such findings led to the first and most influential proposal that temporal relationships are part of what gets encoded in learning, namely, Gibbon's (1977) *scalar expectancy theory* (SET). A key assumption in SET is that animals possess a timing mechanism allowing them to estimate the time to reinforcement (Gibbon & Balsam, 1981).

In the majority of such autoshaping studies food was delivered immediately upon termination of the CS; i.e. a delay conditioning procedure was adopted. One of the few studies of this kind to interpose a delay between CS termination and delivery of food, i.e. a trace procedure, was reported by Balsam (1984), who found that SET needed to be modified in order to fit the results from trace conditioning. However, for both trace and delay conditioning the crucial assumption of SET for the influence of contiguity on learning is that an animal's decision to perform a response is based on the relationship between the time to reinforcement signaled by CS relative to the time to reinforcement signaled by the background context. Thus, a shorter inter-reinforcement, longer trial time or longer trace interval (with all other intervals held constant) all serve to reduce the informational value of the CS and thus the likelihood that the animal will respond. Subsequently data from other preparations have been found to fit these or related timing models (e.g. Gallistel & Gibbon, 2000; Harris, Gharei & Pincham, 2011).

The great strength of timing models (cf. Gibbon & Balsam, 1981; Gallistel & Gibbon, 2000) is that they provide a natural account for the observation that animals can learn, not only to expect an outcome, but also when to expect it, e.g., Pavlov's (1927) inhibition of delay and Skinner's (1938) observation of "scalloping" in fixed-interval schedules. Furthermore, when a delay procedure is employed, appropriately timed anticipatory responses can be observed after very few CS-US pairings (e.g. Balsam, Drew & Gallistel, 2012) and may even be seen after a single pairing (Davis, Schlesinger & Sorenson, 1989; Experiment 4). These and other findings have led to the theory that animals represent the duration of events and their relationships in time using *temporal maps* that are analogous to the representation of spatial relationships (Balsam & Gallistel, 2009): "The strong version of this view is that

temporal relationships between events are constantly and automatically encoded" (Balsam et al., 2012, p.5). Extrapolating from results of the above kind obtained from delay conditioning experiments to events completely separated in time, i.e. trace procedures, these authors have rejected the idea of associative links between event representations and dismissed the conventional contiguity assumption, i.e. that the closer two events are in time, the more likely they are to be associated. Instead they have argued that evidence of the kind discussed in this review is better interpreted in terms of differences in performance; i.e. that animals encode the temporal relationship between two events as easily when they are distantly related in time as when in temporal proximity, but that such learning becomes more difficult to detect as temporal separation increases (Balsam et al., 2012).

The experiments briefly described in this section provide compelling evidence that animals both encode the duration of events and their temporal relationships in relatively impoverished experimental environments where only two highly salient events occur in any session and their pairings are repeated a number of times. It is less clear how temporal coding theories account for 1-trial learning involving multiple events. An example is provided by the experiment related to Revusky's concurrent interference theory that was described in a previous section. Thus, when vinegar solution was presented as an interfering stimulus within the long interval between presentation of saccharin and lithium injection, complete overshadowing (i.e. no aversion towards saccharin) was observed as long as the vinegar solution was as novel as the saccharin solution. Since the temporal relationship between saccharin and lithium injection was constant, why should the novelty or otherwise of the vinegar solution influence whether a saccharin aversion was acquired? Furthermore, temporal encoding theories do not appear to provide an answer to the central

question driving this review, namely: Why does the speed of acquisition of an association between two events, even one that includes information about the events' temporal relationship, decrease as the temporal gap between them increases? The above claim by Balsam et al (2012) appears to imply, for example, that in a single trial a rat would encode the temporal relationship between a tone and a shock delivered 5 min later as effectively as when only a few seconds separated the two events, but encoding of the 5-min relationship would have little or no impact on behavior. If this is a correct interpretation, then it makes the theory very difficult to test. In relation to research supporting Miller's temporal coding hypothesis that was described at the start of this section, it seems very likely that, if the temporal separation of events in Phases 1 and 2 of the Molet et al. (2012) experiment were somewhat greater than 5 s, no evidence for temporal integration would be found.

Concluding comments

As we have seen, over the 150 or so years there have been relatively few attempts to explain why it is difficult to learn that event A is related to event B when these events are separated by more than a few seconds. The most popular suggestion has been the *rapid decay* theory that – at least in the context of animal learning research - is usually attributed to Pavlov. This proposes that the sensory memory of event A decays rapidly so that, if B does not occur until 30s or more have elapsed, no association can be formed between the two events. Until the 1960s almost all research that manipulated the time interval between events in an animal experiment produced results consistent with such a theory. The most dramatic exception was the discovery of long delay taste aversion learning. This inspired the important alternative to decay theory, namely, *concurrent interference* theory, in

which the core idea is that the relationship between A and B can be learned even when they are separated by a long period of time – up to many hours – to the extent that other potentially interfering events are absent (Revusky, 1971).

The demonstration by Odling-Smee (1975) that contextual cues can overshadow a punctate CS in a fear conditioning procedure that includes an interval between the CS and a shock provides a good example of how Revusky's (1971) theory can be applied outside of taste aversion learning, of how a context can be a source of interference and of how interference can be understood within associative theories such as Rescorla and Wagner (1972) and its successors. However, these associative theories, notably Wagner's SOP theory and its successors (e.g. Wagner, 1981; Wagner & Brandon, 2001), fail to provide a satisfactory account of evidence from trace conditioning in the preparations – fear and eye-blink conditioning – that have been most popular for obtaining theoretically-relevant data.

The radical alternative to associative theories based on error-correction and competition between stimuli is some form of timing theory, of which the most recent version appears to deny that the temporal separation between two events is an important factor governing whether an animal or human learns that they are related (Balsam et al., 2012). However plausible this claim might be for the simple forms of classical conditioning experiment providing the data base for such theories, it does not seem to provide a persuasive account of why in instrumental conditioning, for example, animals acquire a response much more slowly when the positive consequence of the response is delayed rather than immediate.

In the introduction to this review, we contrasted the view of Pavlov (1927) who emphasized the rapid decay of a stimulus trace – or sensory after-effect – with that of Thorndike (1911) who referred to the 'idea' of a stimulus, implying a more abstract

representation than that implied by Pavlov, and one that could persist much longer in memory than a more peripheral trace. The evidence from long-delay taste aversion learning and the conclusion reached above strongly support Thorndike rather than Pavlov. Nevertheless, we do not yet have a full explanation of why temporal contiguity matters; current evidence suggests that both interference and decay contribute.

Footnotes

1. A much more recent example of long delay learning that does not involve any aversive treatment is the demonstration that hungry rats can acquire a preference for a flavor followed 60 min later by intragastric infusion of a nutrient, 16% maltodextrin solution (Ackroff, Drucker, & Sclafani, 2012).

2. The terms 'proactive interference (PI)' and 'retroactive interference (RI)' used here in the context of Revusky's *concurrent interference* theory refer to serial overshadowing by stimulus X of some target stimulus, T, where PI refers to conditions in which X precedes T and RI refers to conditions where X occurs in the interval between T and the US. This differs from traditional usage in which, for example, PI refers to interference from a previously learned association, A-B, with subsequently learning an association, A-C. In contemporary associative learning research the traditional usage has been employed, for example, by Bouton (1993).

3. The influential real-time model of Pavlovian conditioning by Sutton and Barto (1981) was published in the same year as Wagner's SOP theory. It included very similar assumptions about trace decay, explicitly referring back to Hull's approach to this topic, as did a later development (Sutton & Barto, 1990).

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