Acquired Reinforcement: Implications for Autism

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Abstract

Integration of experimental analyses of behavior and neuroscience provides an interpretation of a substantial number of the diverse behavioral deficits observed within the autism spectrum. To that end, the behavioral and neural conditions under which experience changes the environmental guidance of behavior are first described, that is, the conditions under which learning occurs. These findings lead to the conclusion that acquired reinforcers—events that function as reinforcers as the result of individual experience—satisfy the same requirements and ultimately engage the same neural system as unconditioned reinforcers. Acquired reinforcers are critical to the development of complex behavior and some of the behavioral problems seen in autism may be due to these deficits. Specific consequences of these deficits are described—including effects on automatic reinforcement, joint control, and joint attention. Environmental as well as genetic factors can produce neurodevelopmental errors that impair acquired reinforcement, and a possible such factor is identified.

Keywords: autism; acquired reinforcement; neural mechanisms of reinforcement; automatic reinforcement; joint control; behavioral cusps

Our goal is to describe the biobehavioral processes by which experience changes the environmental guidance of behavior and then to use these findings to understand some of the diverse behavioral deficits observed within the autism spectrum. The likelihood that a specific behavior occurs in the present environment is dependent on its consequences in the past in that environment. In the field of learning, the process whereby this occurs is called r*einforcement* and the effective consequences *reinforcers*. Experimental work has achieved a compelling understanding of the reinforcement process using reinforcers that affect behavior as the result of evolution through natural selection. Such reinforcers are termed *unconditioned* reinforcers in that their ability to function as a reinforcer is not dependent on events occurring within the experimental procedure. Unconditioned reinforcers arise from experiences that are common in the history of a species and contribute to its survival and reproduction—such as access to nourishment or sexual activity given appropriate establishing conditions (e.g., deprivation). Experimental analyses of reinforcement generally employ unconditioned reinforcers, but it is clear that the environmental guidance of most human behavior is not the product of such consequences, at least directly. If the reinforcement process is to provide fundamental insights into the origins of human behavior, then it must incorporate acquired reinforcers. Acquired reinforcers are events that function as reinforcers as the result of specific experiences of the individual. (The term *acquired* reinforcer is intended to include both conditioned reinforcement studied with operant/instrumental procedures and higher-order conditioning studied with Pavlovian/classical procedures; e.g., Gibbs, et al., 1991).

Unconditioned reinforcers, such as food, water, sexual contact, and release from discomfort, are adaptive because they shape behavior that leads organisms to thrive and successfully reproduce in harsh environments where goods are scarce and competition fierce. But thanks to scientific and technical advances, most people in modern societies live free from great privation. When one's primary needs are met secondary needs become increasingly important, and these vary according to one's personal history. People may value money, prestige, good grades, number of twitter followers, fashionable clothes, rare stamps, fine art, kitchen gadgets, or a fistful of aces. The varieties of human motivation are almost limitless, and most of the relevant behavior is shaped and maintained by acquired reinforcers.

Acquired reinforcers are central to complex behavior, that is, behavior that must occur in patterns, sequences, or hierarchies in order to achieve a conspicuous result. Placing one fieldstone on top of another is a relatively simple behavior; piling fieldstones in such a way as to make a stone wall requires sensitivity to shapes, contours, centers of gravity, surface areas, and relative sizes. Moving a piece of wood across a board is a simple behavior; placing a knight on a square in a chess game requires sensitivity to its position relative to each of the other pieces on the board and its function in achieving a subtle advantage, possibly long delayed, in service of a still more distant goal, impossible to foresee in detail, of checkmating the opponent's king. In any such sequence of behavior, a stimulus typically serves as both as an acquired reinforcer for one behavior and a discriminative stimulus for the next.

Any deficits in the process whereby arbitrary stimuli become acquired reinforcers will have far-reaching implications. Autism is a syndrome with a wide variety of manifestations, but abnormalities in acquired reinforcement are plausibly relevant to many cases. Deficits in social reinforcers are characteristic of the syndrome, leading in turn to deficits in joint attention, language acquisition, interactive play, normative facial expressions, and other social behavior. However, it is not unusual to observe excessive control by specific acquired reinforcers: vestibular, proprioceptive, or visual reinforcers may lead to repetitive rocking, head movements, or hand flapping, while visual patterns may lead to an unusual preoccupation with aligning and adjusting objects.

In this article, we describe the biobehavioral processes of unconditioned reinforcement, their intimate relation to those of acquired reinforcement, and the relationship between discriminative stimuli and acquired reinforcers. Based on these findings, we propose that deficits in the process of acquired reinforcement provide insight into the origins of much autistic behavior and then explore some of the implications of these deficits.

Behavioral Analysis of Reinforcement

The reinforcement process is studied using two distinguishable experimental procedures. In the first—the Pavlovian or classical/respondent procedure—a specified *stimulus* precedes the unconditioned reinforcer. In the second—the Thorndike/Skinner or instrumental/operant procedure—a specified *behavior* precedes the unconditioned reinforcer.

Contiguity Requirement

Findings from both procedures indicate that in order for an unconditioned reinforcer to change the likelihood of a response in the experimental environment, it must occur during or within no more than a few seconds following the preceding event, whether it be a stimulus or a response (see Gormezano & Kehoe, 1981). This illustrates the *contiguity* requirement of the reinforcement process. (Apparent counterexamples such as taste aversions and behavior-system conditioning may also be understood as consistent with the contiguity requirement, see Donahoe 2017, pp. 304-305)

The necessity of contiguity in the reinforcement process poses a challenge to everyday accounts of human behavior. As examples, an office worker is conventionally said to work for a paycheck that is awarded much later, and any food later still. Similarly, the admirer who invites another to dinner secures only a much delayed meal and an uncertain social outcome. Neither office work nor dinner invitations are immediately or invariably reinforced by unconditioned reinforcers, yet both occur and persist. Something more is required to explain such behavior than Alexander Pope's aphorism "Hope springs eternal in the human breast."

A clue to the answer is contained in early studies of operant conditioning. In Skinner's work (1938) on the reinforcement of lever pressing by food-deprived rats, he found that the presentation of food immediately following a lever press was relatively ineffective as a reinforcer because of the delay between the lever press and the consumption of food. To address this problem, he first gave the rats "magazine training" in which the clicking sound of the feeder mechanism preceding food came to guide promptly moving toward and consuming the food. Then, when the lever was first introduced into the test chamber and a press immediately produced the click, lever pressing promptly increased—often after a single occurrence. The click had become an acquired reinforcer. In general, acquired reinforcers must also occur very soon after behavior if they are to be effective (e.g., Royalty et al., 1987). Both unconditioned and acquired reinforcers satisfy the contiguity requirement.

Although interpretations of human behavior regularly appeal to acquired reinforcers, laboratory demonstrations sometimes appear evanescent and amenable to alternative accounts. Two characteristics of the laboratory procedures commonly used to study acquired reinforcement are largely responsible for this impression. First, laboratory tests to evaluate acquired reinforcement often employ an extinction procedure in which the unconditioned reinforcer with which the acquired reinforcer was previously paired is omitted. This procedure ensures that only the acquired reinforcer is maintaining behavior during the test (e.g., Saltzman, 1949). However, achieving this laudable experimental goal does so by instituting conditions that differ from those under which acquired reinforcers function in the natural environment. In the natural environment, the reinforcers with which the acquired reinforcer is paired continue to occur. The immediate reinforcing events that maintain the behavior of office workers, such as seeing a job well-done or the praise of co-workers, would soon weaken if the ultimate consequences—a paycheck exchangeable for food and other outcomes—no longer occurred. A second common type of laboratory procedure employs free-operant techniques (second-order schedules) that permit the unconditioned reinforcer to continue to occur, but in a manner that is temporally remote from the acquired reinforcer (e.g., Kelleher & Gollub, 1962). With free-operant techniques, stimuli that serve as acquired reinforcers maintain that function with respect to the behavior that precedes them, but they may also acquire a discriminative function for the behavior that follows them (e.g., Dinsmoor, 1950; Schoenfeld et al., 1950). Disentangling the reinforcing from the discrim-

inative effects of a stimulus can prove difficult, and questions arise whether the observed behavior is attributable to the discriminative or the reinforcing function (cf., Shahan, 2010). Despite these complications, very comprehensive reviews of acquired reinforcement have concluded: "The neglect of the concept of conditioned reinforcement has been unfortunate, both because of its potential impact on the status of behavior theory as a force in contemporary psychology and because the available evidence speaks strongly in its favor" (Williams, 1994a, p. 473; Williams, 1994b).

Discrepancy Requirement

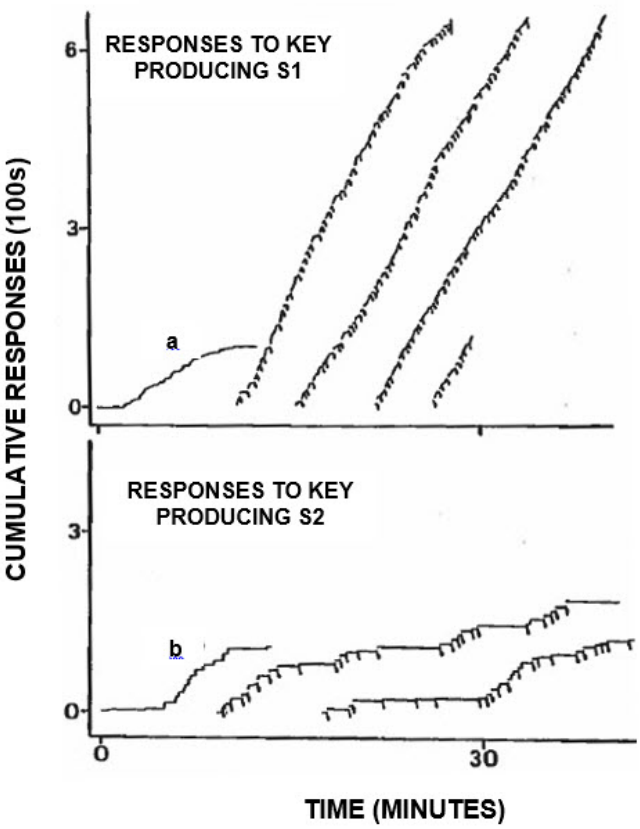
Beginning with research in the latter half of the preceding century, a second requirement for reinforcement was identified. Using both classical (Kamin, 1968, 1969) and operant (Vom Saal & Jenkins, 1970) procedures, it was found that when a response was previously conditioned to a stimulus (S1) and a second stimulus (S2) was subsequently introduced coincident with the first and the reinforcer remained the same, then the second stimulus gained little or no control of the response. Conditioning of S1 *blocked* conditioning of S2. The failure of S2 to gain control occurred despite the fact that the temporal relation of S2 to the reinforcer satisfied the contiguity requirement. Something in addition to contiguity was required.

Further research revealed that conditioning to S2 failed to occur because S1 already controlled the behavior evoked by the reinforcing stimulus when S2 was introduced. The difference between the conditioned response evoked by S1 and the response evoked by the unconditioned reinforcer did not differ sufficiently for S2 to become a conditioned/discriminative stimulus. Thus, in addition to temporal contiguity, the putative reinforcer had to evoke a behavioral change—or *discrepancy*—to engage the reinforcement process. Note that the discrepancy requirement enforces an economy in the learning process: New environment-behavior relations are learned only when the reinforcing stimulus produces a sufficient change in ongoing behavior. An appreciation of the role of discrepancy in the acquisition of new environment-behavior relations was primarily due to the work of Robert Rescorla and Allan Wagner (1972) who cast the discrepancy in associationist terms. An appreciation of the behavioral nature of the discrepancy was gained in subsequent work (e.g., Donahoe & Vegas, 2004; McNish et al., 1997; Stickney & Donahoe, 1983). The use of unconditioned reinforcers, whose presentation evoked a readily measurable response, was critical to reaching this more precise understanding.

The finding that a behavioral discrepancy is required for reinforcement with unconditioned reinforcers raises the question of whether the same holds true for acquired reinforcers. To address this question, Palmer (1988) devised a procedure which paralleled that used by Kamin in his discovery of the role of discrepancy with unconditioned reinforcers, but modified to secure a measure of acquired reinforcement. For a putative acquired reinforcer to occur in an operant procedure, the response must already be in the behavioral repertoire of the learner. To ensure that this was the case, two responses were first conditioned using an unconditioned reinforcer (food) and then extinguished until they occurred at a very low frequency. The following procedure was then instituted for the two concurrently available responses. Responses for experimental subjects were first conditioned using Kamin's blocking procedure: S1 was paired with food followed by further sessions in which S2 was introduced coincident with S1. The simultaneous S1/S2 compound stimulus continued to be paired with food. In a test session to evaluate the role of behavioral discrepancy in acquired reinforcement, the opportunity to make either of the two concurrently available responses was reinstated. One response produced brief presentations of S1; the other response produced brief presentations of S2. As shown in Figure 1, the response that produced S1 increased rapidly in frequency and persisted throughout the test session whereas the response that produced S2 occurred infrequently and was absent altogether during substantial portions of the test session. Thus, the findings with acquired reinforcement are consistent with those with unconditioned reinforcement: For both unconditioned and acquired reinforcement, the putative reinforcer must not only be contiguous with a prior stimulus or response but it must also produce a change in ongoing behavior (cf. Vandbakk et al., 2020).

Figure 1.

Cumulative number of key-pecking responses to either of two response alternatives during a test session following conditioning to S1 and then simultaneous compound S1/S2 conditioning.



*Note. During initial operant conditioning, pecking by a pigeon of either of two illuminated response keys produced access to grain, ensuring that both responses were within the response repertoire. Pecks to the illuminated keys were then extinguished until responding occurred at a low level. With the keys no longer illuminated, S1 was paired with grain followed by simultaneous compound conditioning to the S/S2 stimulus paired with grain. The stimuli serving as S1 and S2 were either a diffuse red light or a tone, counterbalanced across subjects. During the test session for the conditioning reinforcing function of S1 and S2, the response keys were again illuminated and, following a brief initial period (designated **a** and **b**) in which pecking the illuminated keys was again extinguished, pecking one key occasionally produced a brief presentation of S1 while pecking the other key occasionally produced a brief presentation of S2. The stimuli were produced on a variable-interval, 15-s schedule indicated by a downward tick on the graphs. All subjects in the experimental group made more responses to the alternative producing S1 than to the one producing S2, a pattern not shown in control groups. Adapted from "The Blocking of Conditioned Reinforcement," by D. C. Palmer, 1988, Unpublished doctoral dissertation. University of Massachusetts/Amherst, Amherst, MA.*

Neuroscientific Analysis of Reinforcement

The neuroscientific analysis of reinforcement must satisfy two seemingly contradictory behavioral constraints: Reinforcers must be capable of strengthening a wide and relatively arbitrary range of relations between environmental and behavioral events while simultaneously confining the strengthened relation to

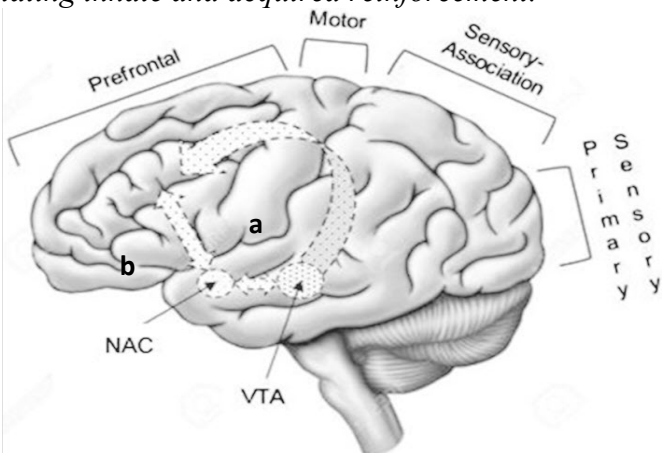
the specific events that are contiguous with the reinforcer. The neural mechanisms of reinforcement accomplish both goals.

Neural Mechanisms of Unconditioned Reinforcement

Figure 2 is a schematic representation of a lateral view of the human cerebral cortex. Environmental events stimulate receptors that give rise to pathways that ultimately activate neurons in primary-sensory and sensory-association areas. In turn, these sensory areas give rise to other pathways that project to the motor and prefrontal areas and, from there, to pathways projecting primarily to the spinal cord leading to observable behavior. (This description omits recurrent pathways; Fuster, 2015.) The focus of this presentation is the modification of synapses between neurons from sensory areas to prefrontal and motor areas. (A more comprehensive account is presented in Donahoe, 2017.) The strengths of these synaptic connections (i.e., synaptic efficacies) must necessarily be among those that change when the environmental guidance of behavior changes.

Figure 2

Schematic presentation of the human cerebral cortex identifying major functional areas and the subcortical structures mediating innate and acquired reinforcement.



Note. Innate reinforcers activate neurons in the ventral tegmental area (VTA) whose projections to the prefrontal cortex liberate the neuromodulator dopamine. Dopamine produces changes in the strength of synaptic connections between co-active neurons in the prefrontal cortex. Prefrontal neurons project to motor areas for behavior and to the nucleus accumbens (NAC) for acquired reinforcement. NAC then projects to the VTA. The net result is that both innate and acquired reinforcers engage the same VTA reinforcement system. See the text for discussion of the cortical regions designated by ***a*** *and* ***b****. (The presentation is not intended to be anatomically correct regarding the various lobes of the cortex, e.g., the area designated Primary Sensory includes only vision). Adapted from Donahoe, J. W. (2017). "Behavior analysis and neuroscience: Complementary disciplines," Journal of the Experimental Analysis of Behavior, 107(3), p. 306*

Unconditioned reinforcers, including many drugs of addiction, ultimately activate neurons in a subcortical group of neurons within the ventral tegmental area (VTA) (Wise, 2002). As shown schematically in Figure 2, the VTA is the origin of neurons that project throughout the prefrontal cortex. These VTA neurons play a vital role in the reinforcement process: (a) their projections are widely distributed within the prefrontal cortex (Matsuda et al, 2009) and (b) numerous varicosities along these projections liberate the neuromodulator dopamine when VTA neurons are activated (Liu et al., 2018). The dopamine molecules diffuse throughout the prefrontal cortex but endure for only a few seconds before being degraded (Yagishita et al., 2014). Dopamine is necessary to modify synaptic efficacies in the frontal lobes and its diffusion

permits reinforcers to affect a wide range of different environment-behavior relations. Moreover, the brief duration of the dopamine molecules is consistent with the contiguity requirement.

Although many synaptic efficacies are *potentially* eligible for modification by reinforcer-instigated dopamine, modification is restricted to those synapses between recently co-active pre-synaptic and post-synaptic neurons. Of necessity, such synapses include—but are not exclusively limited to—synapses between neurons that mediate the reinforced environment-behavior relation. Synaptic efficacies may increase, termed long-term potentiation (LTP) (Bliss & Lømø, 1973) or decrease, termed long-term depression (LTD) (Lynch et al, 1977). Over time, and in the presence of dopamine, the concerted effects of the cellular processes producing LTP and LTD tend to restrict the efficacious synapses to those that mediate the reinforced environment-behavior relation. In summary, the diffusion of dopamine potentially enables a wide range of environment-behavior relations but substantial synaptic efficacies persist for only those synapses between neurons mediating the behavior reinforced in that environment.[1]

Neural Mechanism of Acquired Reinforcement.

As shown by behavioral research, reinforcement of an environment-behavior relation strengthens that relation but also establishes the discriminative/conditioned stimulus as an acquired reinforcer. Neurophysiological studies indicate that discriminative stimuli not only activate pathways from sensory areas to the prefrontal cortex, but also from the prefrontal cortex to the nucleus accumbens (n. accumbens) and thereafter to the VTA (Sabatinelli et al, 2007; Wilson & Bowman, 2004). Furthermore, lesions in the prefrontal cortex of primates have been shown to eliminate the acquired reinforcing effect of discriminative stimuli without impairing the reinforcing effect of unconditioned reinforcers (Pears et al, 2003). By this means, *discriminative stimuli become able to function as acquired reinforcers through ultimately activating the same VTA neural system of reinforcement as unconditioned reinforcers* (cf. Ikemoto & Panksepp, 1999; Salamone & Correa, 2002;).

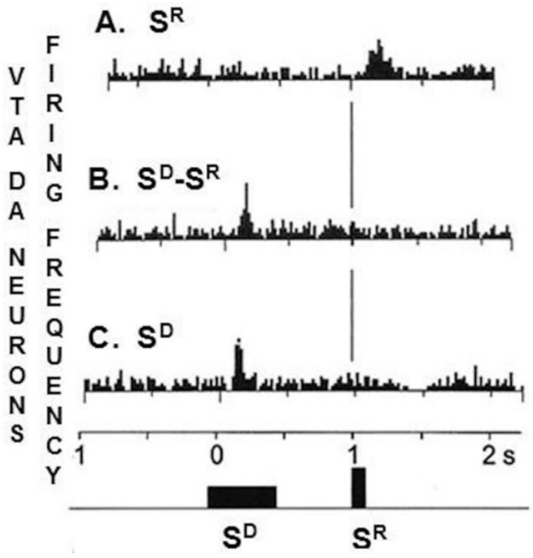
The foregoing account is supported by research using electrophysiological recordings of neural activity in the VTA of primates (e.g., Schultz, 1997; Schultz et al., 1993). Figure 3 depicts the frequency of firing of dopaminergic neurons in the VTA during an experiment in which a manual response in the presence of a visual stimulus produced a liquid reinforcer. As shown in A, at the beginning of the experiment

[1] The following is an overview of the cellular processes by which LTP and LTD occur based on a survey of the relevant literature (e.g. Frey, 1997; Shindou et al, 2019). To achieve better control of events, this research typically employs isolated sections of neural tissue. The sections contain neurons with receptors for the neurotransmitter glutamate, which is the primary excitatory transmitter in the brain, and axons from neurons liberating the neuromodulator dopamine. These dopaminergic neurons arise from the VTA or substantia nigra pars compacta, both of which are activated by reinforcers. When stimulation of a pre-synaptic neuron is paired with firing of the post-synaptic neuron in the presence of dopamine, glutamate AMPA receptors on the post-synaptic neuron undergo LTD. That is receptors on the post-synaptic neuron become less responsive to glutamate. Stimulation of a pre-synaptic neuron paired with firing of the post-synaptic neuron and the time-constrained application of dopamine produces LTP (within 2 s in the relevant experiment; Shindou et al, 2019) and not when introduced either earlier or later. Neither LTD nor LTP occur when only one of the paired neurons is stimulated or when the pre- and post-synaptic neurons are stimulated in reverse order. In addition to the AMPA receptor, high-frequency stimulation of the pre-synaptic neuron engages a second type of glutamate receptor on the post-synaptic neuron, the NMDA receptor. Engagement of the NMDA receptor initiates a cascade of intracellular events ("second messengers") that act on genetic material in the cytoplasm and/or the cell nucleus to initiate protein synthesis. These proteins migrate to the AMPA receptors of the post-synaptic neuron where they produce long-lasting potentiation of those receptors that had been previously "tagged" by glutamate stimulation. The molecular tag endures for several hours, long enough for protein synthesis to occur. Tagging appears to occur with either low- or high-frequency stimulation whether or not the NMDA glutamate receptor is engaged. The foregoing account is consistent with experimental findings but a full understanding of the cellular/molecular processes involved in synaptic plasticity remains incomplete.

the reinforcer elicited a burst of firing of VTA neurons. (Bursting is required for dopamine to be liberated by VTA neurons; Grace et al., 2007). As shown in B, after conditioning had occurred the burst of firing was now initiated by the discriminative stimulus, *not* the reinforcing stimulus. As a consequence, the discriminative stimulus could now function as an acquired reinforcer. Finally, as shown in C, when the discriminative stimulus was *not* followed by the reinforcing stimulus, the frequency of firing of VTA neurons was *decreased*. (This last result is consistent with the behavioral phenomenon of blocking.)

Figure 3

Frequency of firing of VTA dopaminergic neurons at various points during conditioning



Note. A. Response to the reinforcing stimulus $\boldsymbol{S^R}$ *at the outset of conditioning. B. Response to the discriminative stimulus* $\boldsymbol{S^D}$ *followed by the* $\boldsymbol{S^R}$ *after conditioning. C. Response to* $\boldsymbol{S^D}$ *when presented alone after conditioning showing the inhibition of firing when the* S^R *was omitted. Data from Schultz, W. (1997). Adaptive dopaminergic neurons report the appetitive value of environmental stimuli in J. W. Donahoe & V. P. Dorsel (Eds.) (1997). Neural-network models of cognition: Biobehavioral foundations (pp. 317-335). Amsterdam, Netherlands: Elsevier Science Pres*s

Two examples illustrate the important role played by acquired reinforcement in the interpretation of human behavior. Activity of neurons in region **a** of the prefrontal cortex (see Figure 2) control movements of the tongue and lips during vocalizations. Research indicates that the babbling sounds of infants soon begin to approximate the speech sounds (phonemes and intonation patterns) characteristic of the language of their caretakers (Jusczyk, 1997). These are the speech sounds emitted by caretakers as they feed and otherwise tend to the infant. Through the confluence of these events, such sounds become discriminative/conditioned stimuli. Subsequently, when infants make tongue and lip movements during babbling, these articulatory movements are strengthened by acquired reinforcement to the extent that they produce acoustic stimuli that resemble those of the caretakers' vocalizations. These movements are *automatically* strengthened through acquired reinforcement. This mechanism plays a critical important role in language acquisition (Donahoe & Palmer, 1993/2019; Skinner, 1957; Vaughan & Michael, 1982). As a second example, neural activity in region **b** is activated by visual stimuli characteristic of the human face (Ishai et al., 2005). These visual stimuli also co-occur with the reinforcing consequences of the behavior of the caretaker and, as a result, come to function as acquired reinforcers. (For a more comprehensive account of the role of acquired reinforcement in human behavior, see Donahoe & Palmer, 1993/2019.)

Note that in order for discriminative stimuli to function as acquired reinforcers, they must activate neural pathways in the prefrontal cortex that ultimately produce activity in the VTA. If such pathways are

reduced or absent, the affected discriminative stimuli may be less able to function as acquired reinforcers and, therefore, to assume the central role that such reinforcers play in complex behavior.

Acquired Reinforcement and Autism

Autism is commonly designated an autism *spectrum* disorder (ASD) because of the wide variety of behavioral deficits it manifests. These include deficits in social behavior—such as maintenance of eye contact during interactions with others and verbal communication—such as delay in language acquisition. Here we examine the relation between some of the diverse behavioral deficits observed within the autism spectrum and the similarly diverse effects of deficits in the biobehavioral processes of acquired reinforcement.

The development of noninvasive imaging techniques provides structural and functional information from the living brain of autistic persons. Using diffusion tensor imaging (DTI), decreases in the number and distribution of pathways from neurons within the prefrontal cortex to the n. accumbens have been found with ASD subjects (Langen et al, 2012; see also Velmeshev et al, 2019). This is consistent with the proposal that there is a deficit in the stimuli that can function as acquired reinforcers for persons with ASD.

Further evidence of this deficit is provided by a second imaging technique—functional magnetic imaging (*f*MRI). When neurons are activated, the blood supply to that region of the brain increases and *f*MRI detects this increase. Which particular pathways are decreased from the prefrontal cortex to the n. accumbens determines the nature and extent of the stimuli able to function as acquired reinforcers. As a demonstration of the reduced capability for acquired reinforcement, autistic and control subjects were presented with a paired-associate learning task during which *f*MRI measures were taken (Langen, 2012). For most word pairs, choice of a correct response was immediately followed by the presentation of a picture of a type found to be interesting (reinforcing) to the individual subject in a pretest. For a few word pairs, correct responses were not followed by an interesting picture but by a dollar sign ($). Prior to the paired-associate task, subjects were told that a correct response would earn a dollar for each appearance of the $ sign. The $ sign was intended to function as an acquired reinforcer. For control subjects, the *f*MRI indicated that the $ sign activated neurons in the n. Acc. as strongly as did interesting pictures. However, for ASD subjects activation of the n. accumbens by the $ sign was greatly reduced, although these subjects reported that they knew that a dollar would be received for each occurrence. Thus, for ASD subjects the dollar sign functioned as a discriminative stimulus but not as an acquired reinforcer. By contrast, when ASD subjects received an interesting picture after a correct response, activity in the n. Acc. increased to the same extent as for control subjects. It is noteworthy that interesting pictures for ASD subjects were generally of nonsocial objects such as complex machines, automobiles, and computers. Different types of pictorial stimuli functioned as acquired reinforcers for autistic and control subjects. In summary, through their effects on different areas of the prefrontal cortex, some pictorial stimuli activated neurons in the n. accumbens and functioned as acquired reinforcers for ASD subjects whereas the stimulus of a dollar sign did not. The neurodevelopmental/genetic factors that determine which particular prefrontal-to-n. accumbens pathways are reduced are unclear.

A deficit in the number and types of stimuli that can function as acquired reinforcers for ASD persons provides an interpretation of many of the diverse deficits observed within the spectrum. This conclusion was foreshadowed in the pioneering work of Ivar Lovaas (1987) in which the behavior of severely autistic children was initially modified only by using unconditioned reinforcers (food introduced directly into the mouth). As an illustration of the effects of such a deficit, if the neural activity accompanying articulatory movements does not also give rise to pathways that access the n. accumbens, then automatic reinforcement of the infant's articulatory movements cannot occur when the infant hears its own vocalizations.

Other behavioral effects of neurodevelopmental errors in autism

The genes implicated in the neurodevelopmental deficits that affect acquired reinforcement have other behaviorally significant effects because many of them affect synapse formation (Yoo, 2015). Consequently, their effects on neurodevelopment are pervasive. Neurodevelopment involves complex processes that are incompletely understood, but the basic challenge it poses is clear: The human brain with its perhaps 100 billion neurons, each one of which averages some thousands of synaptic contacts, cannot be specified in point-to-point detail by the approximately 30,000 genes in the human genome (Luo, 2021). Faced with this constraint, the various local processes that affect neural growth are supplemented by initially generating a surplus of potential neurons: From a relatively smaller number of progenitor cells, large numbers of incipient neurons are proliferated, with those neurons enduring that form synaptic contacts with other neurons and those neurons dying that do not. Whether synaptic contacts form between neurons depends on interactions between receptors on the candidate neurons and the effect of neurotransmitters on those receptors. Whether a given pathway forms or fails to form is the outcome of processes that are, in part, probabilistic.

A further outcome of these neurodevelopmental processes is considered here—the processing of aversive stimuli by the *amygdaloid complex* (LeDoux, 2000). The amygdala is a subcortical structure that receives dopaminergic projections from the VTA in which dopamine also alters synaptic efficacies between co-active neurons.

A commonly noted characteristic of autistic persons is the avoidance of direct eye contact (McGlensey, 2016). With autistic persons, *f*MRI measures obtained from the amygdala when viewing pictures of faces indicated that the amygdala was strongly activated not only by threatening facial expressions, but also by expressions ordinarily considered positively engaging and socially rewarding. The difference from control subjects in the activation of the amygdala was most marked for fear-arousing faces, but the difference was also present for happy faces displaying eye contact (Hadjikhani et al, 2017). For autistic subjects, amygdaloid neurons over-respond to stimuli considered positively engaging and socially rewarding by control subjects (McGlensey, 2016).

In general, if neurodevelopmental errors occur in any structure that is the target of the VTA reinforcement system, then the usual function of that structure may be altered. This includes perceptual processing in sensory-association cortex (Feldman et al, 2018, cf. Krieckhaus et al, 1992) and the coordination of behavior, including that more subtle behavior of thinking, in the cerebellum (Becker & Stoodley, 2013; Flace et al, 2021).

A Possible Environmental Risk Factor for Autism

Although genetics critically contributes to autism spectrum disorder (ASD), environmental factors also play a role. A survey by the National Institutes of Mental Health of the incidence of ASD found that the reported frequency of the diagnosis increased by 175% from 2000 to 2020 (Maenner et al, 2020). Although such an increase undoubtedly reflects changes in awareness of the disorder and refinements in diagnostic criteria, the rapidity of the change exceeds that likely from genetic factors alone and suggests the effects of some environmental variable(s) on neurodevelopment.

The most common neural receptor is the CB1 cannabinoid receptor (Busquets-Garcia et al., 2018; Galve-Roperh et al., 2009; Hadland et al., 2015). During neurodevelopment the CB1 receptor, which is located toward the growing tip (axon) of neurons, modulates the release of neurotransmitters (Iversen, 2008). Laboratory studies reveal that the CB1 receptor can affect the occurrence of LTP, the process whereby synaptic connections form (Silva-Cruz et al., 2017). In short, the CB1 receptor plays a central role in the development and functioning of the nervous system (de Salas-Quiroga et al., 2015; Hillard, 2015; Wu et al., 2011). Studies of the neural development of children who later become autistic reveal that their fetal frontal lobes are initially larger but following birth become smaller than control subjects (Rivkin et al, 2018; Rubenstein, 2011; Wu et al., 2011). This suggests that some early proliferating neurons have failed to make functional synaptic connections and have died.

A number of observations are consistent with the view that marijuana may pose an environmental risk factor for ASD (e.g., Corsi et al, 2020): Over time, marijuana has increased in both usage and potency.

Almost half of the psychoactive compound in marijuana (trans-Δ^9-tetrahydrocannabinol, or THC) in the maternal bloodstream crosses the placenta and fetal blood-brain barrier (Grotenhermen, 2003; Shiono, Klebanof, Nugent, et al., 1995) and—most importantly—THC is known to act on the CB1 receptor. Further, the incidence of autism is higher in the offspring of mothers who habitually smoke marijuana (Corsi et al, 2020; Finch, 2019; Jung et al., 2017). Correlational findings are limited in their implications, however, because they are subject to alternative accounts. For example, prior to pregnancy, women who smoke marijuana may differ in other respects from mothers who do not smoke.

Experimental findings are more persuasive regarding the relation between habitual marijuana use and autism, and they also indicate that THC is a possible risk factor (e.g., Donahoe, 2018). THC binds to the CB1 receptor and, when the environment introduces an exogenous compound that binds to a receptor, the endogenous production of that transmitter is typically reduced (Hsieh et al., 1999; cf. Eikelboom & Stewart, 1982). Reduction in the synthesis of a gene product can be produced by attaching a chemical group, e.g., a methyl group (—CH_3), to the gene(s) for that transmitter. (The gene itself is not altered.) Methylated CB1 genes have been found in the n. accumbens of animals exposed to THC and this structure is critical for acquired reinforcement (Watson et al, 2015). In autistic persons, methylated genes are found within the frontal lobes as well as the n. accumbens, and have been proposed as a fundamental factor in autism (Tremblay & Jiang, 2019). Which specific prefrontal pathways are affected during neurodevelopment are a function of both methylation and genetics and would vary with the nature of the behavioral deficits observed in the individual case.

The effects of environmental factors on gene expression (*epigenetic* effects) are not confined to the generation directly subject to the exogenous effects (Curry, 2019). In animal studies, rodent mothers experiencing pregnancy within a stressful environment sustain a reduction in their response to stress through methylation of the relevant genes. Subsequently, these methylated genes are also present in their offspring. Moreover, the same methylated genes also appear in the *offspring* of their offspring (Watson et al. 2015)! (Methylation may be adaptive in the natural environment if the stressful factor that methylated the genes of the mother also occur in the environment of the offspring.) Recent studies with humans have yielded a corresponding result: The methylation-produced decrease in the production of the neurotransmitter for the CB1 receptor occurred not only in mothers exposed to THC, but also in their offspring (Karlson et al, 2018).

Understanding Autism as a Deficit in Acquired Reinforcement

Findings from the study of behavior, neuroscience, genetics, and epigenetics are consistent with the view that autism may be fruitfully viewed, in substantial part, as a deficit in acquired reinforcement. Here, we explore some of the implications of that conclusion for understanding autistic behavior.

Behavioral cusps

Rosales-Ruiz and Baer define behavioral cusps as "any behavior change that brings the organism's behavior into contact with new contingencies that have even more far-reaching consequences" (1997, p. 533). A behavioral cusp is analogous to a doorway into a room full of novel reinforcers that can shape new behavior. Just as the evolution of the lung enabled organisms to exploit new ecosystems previously out of reach, learning to walk, learning to talk, and learning to read open new worlds of experience to children that will lead to ever more cusps in the development of cumulative hierarchies of skills (Hixson, 2004). Achieving behavioral cusps can be viewed as the chief behavioral process underlying child development (Rosales-Ruiz & Baer, 1996). Early deficits or irregularities in acquired reinforcement might stall this developmental trajectory at early stages.

Evidence to support this thesis can be found in studies that investigate the role of acquired reinforcers in achieving developmental milestones in autistic children. Greer and his colleagues have shown that establishing various forms of correspondence between stimuli as acquired reinforcers can lead to the

emergence of developmental milestones For example, Du and Greer (2014) showed that establishing correspondence between motor and visual patterns in mirror tasks as a reinforcer led to the emergence of novel imitative behavior in autistic children. Longano & Greer (2015) showed that establishing relevant visual and auditory stimuli as acquired reinforcers led to the emergence of orienting responses that, in turn, led to the acquisition of both productive and receptive naming behavior.

Other examples of behavioral cusps are joint attention, joint control, and sensitivity to parity between the stimulus properties of one's own behavior and that of others, leading to automatic reinforcement.

Joint Attention

Although joint attention requires the interaction of two or more parties, we are concerned here with the moment-to-moment behavior of the individual. For present purposes we can define it as the behavior of monitoring the behavior of another with respect to some object or event. Common examples would be checking the gaze of another to see if that person is also engaged by an object of interest, following the gaze of another to a hitherto unobserved object or event, or alerting someone else to such an event. Monitoring eye gaze, pointing, and reciprocal vocalizing are common indices of joint attention. Since one's gaze tends to be fixed on things that are interesting, important, or relevant in some context, following the gaze of another is likely to be reinforced by those variables. This is particularly likely in the case of a naïve child and an experienced caregiver in a changing environment. Successful modelling and instruction usually entail joint attention and often require it. Moreover, joint attention is likely to set the occasion for conversation or narration. Through myriad experiences of these sorts, indices of joint attention become acquired reinforcers in typical children, and in turn, the children steadily acquire new skills and broaden their experience. The social event of "sharing experiences," in itself, may become reinforcing, and indeed this outcome, however difficult to operationalize, is commonly considered an indispensable feature of joint attention (Dube, et al. 2004).

Joint attention is important in the acquisition of language (Tomasello, 1988), and deficits in joint attention have been postulated to be a characteristic feature of autism (Baron-Cohen, 1989; Carpenter et al., 2002; Mundy, 1995). The deficits can appear in both responding to and initiating joint attention, that is, the tendency to follow the attention of another and the tendency to draw the attention of others to an interesting event (Holth, 2005), but deficits in initiating joint attention tend to be especially pronounced in autistic individuals.

According to a contingency analysis of joint attention by Dube, et al., (2004), initiation deficits in the autistic child may arise from the failure of adult cues to serve discriminative or acquired reinforcing functions. The social cues of the adult typically become both discriminative stimuli for orienting to and engaging with an object of interest as well as acquired reinforcers for orienting to the adult. Social cues are subtle, and tiny differences in facial expression, tone of voice, and eye orientation can serve very different functions, so even small deficits in social behavior may have disproportionately large effects on the repertoire of a child.

In a study of joint attention in autistic children, baseline observations confirmed that measures of responding to joint attention cues and initiating joint attention fell substantially below age norms, as would be expected if deficits in acquired reinforcement are characteristic of the syndrome (Isaksen & Holth, 2009). The authors then set up operant discrimination contingencies to establish social cues from adults as both conditioned reinforcers and discriminative stimuli. All children showed substantial and ecologically valid increases in scores on relevant behavior scales, in some cases exceeding age norms. Furthermore, on a one-month follow-up evaluation of initiating joint attention, all children scored as well as, or higher than, they did immediately after training. This suggests that their newly acquired sensitivity to social reinforcers was being supported by natural contingencies.

This study raises two points relevant to our thesis. First, deficits in joint attention were clearly specifically linked to deficits in acquired reinforcement, supporting the hypothesis that such deficits are

characteristic of autism. Second, acquired reinforcement emerged from an operant discrimination procedure, that is, one that established the target stimulus as a discriminative stimulus, rather than through stimulus-stimulus pairing. (See also Holth, et al., 2009; Vandbakk et al., 2019; Olaff & Holth, 2020). These results correlate well with the neurophysiological data suggesting a relationship between discriminative responding and activation of the n. accumbens However, the experiment also shows that the behavioral deficits can be remediated with contingency management, suggesting that any physiological deficits may not be all-or-none but a matter of degree.

Joint Control

The interplay of discriminative and reinforcing function of stimuli is evident in many commonplace sequential activities such as following multistep instructions. The behavior of shopping for items on a list at the grocery store can serve as a case in point. Finding one item on the list is both reinforcing for one search and discriminative for beginning a search for the next item. This is so commonplace an activity that we are apt to overlook its complexity. If we happen to be engrossed in a podcast as we shop, we are quite likely to walk right past the molasses, though we are "looking for it." That is, "recognizing" molasses, as such, requires not just seeing the jar in our field of view and our having previously read it on a list; we must be "thinking about molasses," or "looking for molasses," or rehearsing "molasses" at the time we see it. Under such conditions, responding to molasses—by saying "molasses!" or by orienting to it and approaching it—has two sources of strength: the visual stimulus and the stimulus properties of our own precurrent behavior. Lowenkron (1991,1998) has dubbed the confluence of two sources of control *joint control* and has shown that it is a discriminable event that can control transitions in behavioral sequences. The onset of joint control serves as both a reinforcer and a discriminative stimulus in search behavior, matching tasks, and many other sequential activities.

Of particular relevance to the present thesis, typically developing children become sensitive to joint control through natural contingencies, but children with autism and other disabilities often do not. For example, in a delayed match-to-sample paradigm, Lowenkron (1988) showed that none of four developmentally delayed children were able to successfully select a visual stimulus that matched a sample stimulus after a delay of as little as 4 seconds. Lowenkron then taught the children to make a distinctive hand sign to each sample stimulus, to hold the hand sign throughout the delay interval, and to hold the sign underneath each comparison stimulus in turn. At the moment of coincidence, i.e., when the hand sign corresponded to the topography of response evoked by the comparison stimulus, he delivered reinforcement, thereby putatively establishing joint control as an acquired reinforcer. Under these conditions, all of the children were able to select the stimulus that matched their hand sign, and they were able to respond correctly in a generalization task when they were taught appropriate hand signs.

Lowenkron's analysis of sequential behavior has been abundantly confirmed with typically developing children and adults in whom the acquired reinforcing and discriminative functions of joint control arose largely from natural contingencies (see Ampuero & Miklos, 2019, for a review). In contrast, children with autism are commonly unable to engage in delayed matching tasks and multistep instructions without remedial interventions (Causin et al., 2013; Tu, 2006; Vosters & Luczinski, 2020).

Automatic Reinforcement

The onset of joint control can be said to be "automatically reinforcing" in the sense that it typically arises from the task itself and does not require mediation by other people (Palmer, 1996; Skinner, 1957; Vaughan & Michael, 1982). A pianist can pick out a pleasing novel tune at the keyboard without acclaim from an audience: variations in the behavior itself generates differentially reinforcing stimuli. Much human behavior is shaped by automatic consequences, including much verbal behavior, modeling, and most motor behavior. Reinforcers mediated by other people can be exaggerated for the novice and attenuated as proficiency develops, but automatically reinforcing stimuli cannot easily be modulated to meet the needs of the learner. As a consequence, any deficits or irregularities in sensitivity to such stimuli can have pervasive effects on development.

As mentioned earlier, autistic children may be susceptible to reinforcement by repetitive stimuli in various modalities, leading to socially inappropriate and often maladaptive rocking, hand-movements, vocalizations, and even head-banging. Since behavior shaped by such reinforcement is clearly maladaptive, it is often unclear how such stimuli become reinforcing. Any irregularities in neural development in pathways leading to n. accumbens offer a possible interpretation of the origin of atypical acquired reinforcers. Fortunately, many studies have shown that children with autism and other disabilities, who have not acquired normative reinforcers through natural contingencies, can frequently acquire them through carefully arranged training procedures (for reviews, see Cló & Dounavi (2020), Lepper & Petursdottir, 2017; Lepper et al., 2013, Petursdottir & Lepper, 2015; see also Greer & Ross, 2009; Greer & Singer-Dudek, 2008).

A particularly important acquired reinforcer in typical development is evidence that one's behavior has matched that of a model. Such matching may be particularly important in language acquisition, not just in the acquisition of words but in grammatical constructions. Parents seldom explicitly instruct children about grammatical norms (e.g., Brown & Hanlon, 1970), but children become effective listeners before they become speakers, and conforming to grammatical norms can be acquired through automatic shaping. For example, young children have acquired the passive voice entirely through automatic shaping, in some cases in the face of explicit parental reinforcement for using the active voice (Dal Ben & Goyos, 2019; Østvik et al., 2012; Wright, 2006).

Concluding Comments

Experimental analyses of reinforcement, conducted at both the behavioral and neural levels of observation, produced a mutually consistent understanding of the contiguity and discrepancy requirements for learning, most particularly with regard to acquired reinforcement. The resulting understanding supports an account of autism that attributes some of the diversity of behavioral deficits observed along the autism spectrum to variable neurodevelopmental errors in the neural mechanisms of acquired reinforcement, with habitual marijuana use a possible environmental risk factor for these errors. Deficits in acquired reinforcement provide insight into the origins of many aspects of autistic behavior.

In addition to these specific findings and their implications, the research exemplifies a general point: Behavioral findings identify critical constituents of the agenda for neuroscience. In the present instance, the behavioral finding that a given environmental event typically acquires both discriminative and reinforcing functions led to a search for the means by which the VTA reinforcement system might be engaged by acquired as well as unconditioned reinforcers. The behavioral blocking effect also led to a search for a means whereby activating the VTA reinforcement system by an unconditioned reinforcer could be blocked by a preceding discriminative stimulus/acquired reinforcer.

A sense of the nature of the contribution of behavioral research to neuroscience may be illustrated with a non-biological example. Electronic circuits can be designed by genetic algorithms that simulate the evolutionary process: A population of candidate circuits is randomly generated, with those circuits retained that most closely approximate a given goal and then disproportionately contribute to the next "generation" of potential circuits (Holland, 1992). For instance, the goal of the genetic algorithm might be to produce a circuit that implements what is called a patterning discrimination in behavioral science (an exclusive-or problem in logic and computer science). A genetic algorithm successfully produces such an electronic circuit; however, the function of the circuit is often not apparent from knowledge of the circuitry alone. It is only upon knowing the contingencies of selection implemented by the genetic algorithm that the function of the circuit can be understood. How much more difficult is understanding the function of neural structures without knowledge of the behavioral phenotype produced by natural selection and selection by reinforcement! Behavioral science provides only a part—albeit a critical part—of the agenda of neuroscience. In the presence instance, a future task for neuroscience is to determine the specific interactions between excitatory and inhibitory neurons within and between the ventral tegmental area and nucleus accumbens that implement the discrepancy requirement.

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