Sighs can become learned behaviors via operant learning

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Abstract

Sighs have important physiological and psychological regulatory functions. These rewarding effects of a sigh potentially reinforce sighing in situations that require physiological and/or psychological regulation. The present study aimed to investigate whether sighs can become learned behaviors via operant learning. In two studies, we manipulated the effect of spontaneous sighs in response to dyspnea relief, by either punishing a sigh by the onset of dyspnea, or not punishing a sigh by continued dyspnea relief. Results show that sigh rates in response to cues predicting the punishment of sighs are 1.20-1.28 times lower than sigh rates in response to cues predicting no punishment of sighs. These findings suggest that sighs can become learned behaviors via operant learning, contributing to both maladaptive sighing, potentially leading to respiratory dysregulation and respiratory complaints, and to adaptive sighing. Furthermore, these findings suggest new clinical practices to increase and decrease sigh rates during breathing training.

Introduction

Breathing plays an essential role in both the etiology and maintenance of anxiety disorders (Meuret, Wilhelm, & Roth, 2001). In panic disorder specifically, the role of sighs contributing to respiratory dysregulation in experimental studies has been well established (Meuret et al., 2001; Meuret, Wilhelm, Ritz, & Roth, 2008; Wilhelm, Trabert, & Roth, 2001c, 2001a; Wilhelm, Gerlach, & Roth, 2001; Martinez et al., 2001; Schwartz, Goetz, Klein, Endicott, & Gorman, 1996; Yeragani, Radhakrishna, Tancer, & Uhde, 2002; Abelson, Weg, Nesse, & Curtis, 2001; Abelson, Khan, Lyubkin, & Giardino, 2008; Grassi et al., 2014). Research has shown that panic disorder patients sigh excessively, leading to chronic hyperventilation and hypocapnia (Wilhelm, Trabert, et al., 2001a), which in turn enhances anxiety symptoms. If excessive sighing in panic disorder patients leads to chronic respiratory dysregulation and symptoms, why do they keep on sighing as frequently as they do? One possible explanation is that sighs are reinforced by their immediate rewarding effects, overriding the effects of hyperventilation and physiological dysregulation caused by excessive sighing on the long term.

Sighs indeed have important rewarding effects. Sighs, i.e. single deep breaths, are essential to maintain healthy physiological and psychological regulation (Li & Yackle, 2017; Ramirez, 2014; Vlemincx et al., 2013a). Physiologically, sighs primarily prevent atelectasis (i.e. the collapse of alveoli when respiration is lacking variability). In doing so, sighs restore lung compliance (Bendixen, Smith, & Mead, 1964; Caro, Butler, & DuBois, 1960; Ferris & Pollard, 1960; Golder, Reier, Davenport, & Bolser, 2001; McIlroy, Butler, & Finley, 1962; Mead & Collier, 1959; Reynolds, 1962), reduce hypoxia and hypercapnia (Bartlett, 1971; Bell, Ferguson, Kehoe, & Haouzi, 2009; Bell & Haouzi, 2009; Cherniack, Euler, Glogowska, & Homma, 1981), and reset healthy respiratory variability (Vlemincx, Van Diest, Lehrer, Aubert, & Van den Bergh, 2010; Wuyts, Vlemincx, Bogaerts, Van Diest, & Van den Bergh, 2011).

Moreover, sighs reset a sympathovagal balance when either sympathetic or parasympathetic activity persistently dominate (Franco et al., 2003; Porges et al., 2000).

Sighs not only improve physiological regulation, but also enhance psychological regulation by facilitating transitions from aversive to less aversive states, such as facilitating relief. For example, instructed sighs decrease self-reported negative affect and craving during smoking withdrawal (McClernon, Westman, & Rose, 2004) and increase self-reported relief (Vlemincx, Taelman, Van Diest, & Van den Bergh, 2010; Vlemincx, Van Diest, & Van den Bergh, 2016), and spontaneous sighs evoke physiological relief by reducing muscle tension, particularly in anxious persons (Vlemincx, Taelman, et al., 2010; Vlemincx et al., 2016). Moreover, sighs not only induce relief, but they also express relief; sighs occur more frequently during induced relief of stress (Soltysik & Jelen, 2005; Vlemincx, Meulders, & Abelson, 2017; Vlemincx et al., 2009) and symptoms (e.g. relief of dyspnea (Vlemincx, Meulders, & Luminet, 2018)). Accordingly, sigh frequency is high during relaxation following tension (Stevenson & Ripley, 1952), and during interruptions of stressful and attentive tasks (Teigen, 2008; Vlemincx, Taelman, De Peuter, Van Diest, & Van Den Bergh, 2011a). Altoghether, these findings suggest that sighs facilitate relief by both inducing and expressing relief.

Given these resetting and relieving effects of sighs, physiological and/or psychological reward in response to sighs may reinforce sighing and therefore increase sighing in situations that require physiological and/or psychological regulation. This way, sighs can be adaptive responses during stress and emotions. For example, sighs occur more frequently in persons who show high stress responsiveness and high anxiety sensitivity (Vlemincx et al., 2017). However, sighing can also become a maladaptive behavior when persons sigh excessively to cope with situations they perceive as stressful or emotional, but that not necessarily require physiological mobilization. For example, panic disorder patients tend to easily perceive safe situations as threatening. Possibly associated with this biased perception of threat, panic patients sigh excessively (Abelson et al., 2008, 2001; Schwartz et al., 1996; Wilhelm, Gerlach, et al., 2001; Wilhelm, Trabert, et al., 2001a, 2001c); they very frequently take a very deep breath that doesn't allow the recovery of carbon dioxide pressure (Wilhelm, Trabert, et al., 2001a), causing chronic hyperventilation and chronic respiratory dysregulation (Meuret et al., 2001, 2008; Wilhelm, Trabert, et al., 2001c, 2001a; Wilhelm, Gerlach, et al., 2001; Martinez et al., 2001; Schwartz et al., 1996; Yeragani et al., 2002; Abelson et al., 2001, 2008; Grassi et al., 2014).

To further understand the role of sighs in normal and dysregulated breathing, particularly in panic disorders, it is essential to better understand the mechanisms that influence sighs. Given that relief elicits reward learning (Seymour et al., 2005), one of those mechanisms may be operant learning. The present study aimed to investigate whether sighs can become learned behaviors by operant learning. Since hyperventilation and hyperventilation symptoms, including dyspnea, are critical in panic disorder (Meuret et al., 2008, 2001), an operant learning paradigm was used inducing dyspnea and dyspnea relief. Previously, we have shown that spontaneous sighs can be systematically elicited by dyspnea relief induced by the presentation of a cue that indicated the offset of a respiratory resistance (Vlemincx et al., 2018). Using this manipulation in the current study, spontaneous sighs were online monitored and detected during the cued offset of a resistance, and either punished by the onset of the resistance (predicted by one of two operant symbols), or not punished by the continued offset of the resistance (predicted by the other operant symbol). This way, participants learned that in response to a specific operant symbol, a sigh would be either punished or not punished. Two studies were conducted. In the first study, sighs were elicited by the offset of a mild resistance and punished by the onset of a very strong resistance. To replicate the findings of the first study, and to examine whether learning of sighs could be found with very mild dyspnea and dyspnea relief, as would be the case in real life, a second study was performed in which sighs were elicited by the offset of a very mild resistance and punished by the onset of that same very mild resistance. In both studies, the critical comparison was made during the test phase; after the learning phase, the learned operant symbols were presented during the cued offset of the resistance, while sighs were no longer punished or not punished. If sighs can be brought under control of cues predicting punishment of sighs, less sighs would occur in response to a cue that predicts the punishment of a sigh than in response to a cue that predicts no punishment of a sigh.

Methods and Materials

Participants

Participants were recruited through the online Experiment Management System of the Faculty of Psychology and Educational Sciences of the University of Leuven, Belgium. Pregnant or breast feeding women and participants with cardiovascular disease, respiratory disease, neurological disease, (a history of) clinical depression or anxiety disorders or medical advice to avoid stressful situations were excluded from participation to the study. Participants were given course credits or fifteen euros in exchange for participation. The experiment was approved by the Ethics Committees of the Faculty of Psychology and Educational Sciences and of the Faculty of Medical Sciences, University of Leuven, Belgium.

In Study 1, 56 participants (36 women, mean (SD) age = 22.94 (4.68), range 18-41) completed the study, whereas 44 participants (29 women, mean (SD) age = 22 (2.88), range 18-34) completed Study 2. Sample sizes were determined by power analysis using G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009) [Study 1: exp($\beta 1$)=1.15 (expecting a low effect size), exp($\beta 0$)=0.33 (predicted base rate of sighing during transitions from a resistance of 20 $cmH_2O/l/s$ to no resistance (Vlemincx et al., 2018), mean exposure=64 (number of trials), α=.05, power=.80); Study 2: exp($\beta 1$)=1.2 (effect size of Study 1), exp($\beta 0$)=0.23 (predicted base rate of sighing during transitions from a resistance of 10 $cmH_2O/l/s$ to no resistance (Vlemincx et al., 2018)), mean exposure=64 (number of trials), α=.05, power=.80)].

Measures

Self-report measures. Dyspnea intensity was rated on a Borg scale from zero (no dyspnea) to 100 (maximally imaginable dyspnea) using a dial.

Respiratory measures. Respiration was measured by means of two respiratory belts around the chest and the abdomen, consisting of embedded hall sensors, connected to a to a NeXus-10 unit (Mind Media B.V.). Respiratory signals were monitored and stored using Biotrace software (Mind Media B.V.).

Respiratory setup

Participants breathed via a face mask which was attached using a head gear. The facemask was connected to a respiratory filter which, in turn, was connected to a non-rebreathing valve and a tube connected to the inspiratory end of the non-rebreathing valve. On the other end of this inspiratory tube, a four-way valve was attached to apply various breathing resistances and different levels of dyspnea.

Procedure

Participants individually signed up to a 2-hour experiment 'Catch your breath' studying the effects of breathing resistances and relief thereof. Upon arrival, participants provided informed consent and completed screening questionnaires. Next, the two respiratory belts were attached, and the instructions to the experiment were explained. Participants were told that they would breathe via a face mask attached to a breathing circuit that allowed the experimenter to control the breathing resistance of the circuit by increasing the obstruction of the circuit. Increasing the breathing resistance would make it more difficult for the participant to breathe in and would increase the effort to breathe in, therefore inducing dyspnea.

It was explained that figures (a circle, triangle or pentagon) on the screen indicated the magnitude of the breathing resistance. Every trial would start with the presentation of a breathing resistance, indicated by one of the figures. When the breathing resistance disappeared, the previous figure would disappear and another figure would be presented. In this figure, one of two symbols (a star or a square) would be presented indicating whether a deep inhalation would be punished or not. One symbol predicted that a deep inhalation during the symbol would be followed by a resistance and thus the experience of dyspnea. The other symbol predicted that a deep inhalation during the symbol would be followed by a period of no resistance and thus breathing freely. Participants were not told which symbol was associated with the punishment of a sigh or no punishment of a sigh.

Participants were asked to continuously rate perceived dyspnea intensity, while sitting motionless but comfortably. After providing the instructions, the face mask was put on and when the participant was comfortably connected to the breathing circuit, the experiment started. After the experiment, the respiratory setup was detached and participants were debriefed.

Design

Figure 1 shows the graphical representation of the design. The experiment consisted of four blocks: two learning blocks (one punishment block, one no punishment block), followed by two test blocks (one punishment block, one no punishment block). Each block consisted of 16 trials. During the trials, figures (circle, triangle or pentagon) indicated the magnitude of the breathing resistances, whereas operant symbols (star vs. square) indicated punishment or no punishment. During all four blocks, each trial started with a resistance phase during which participants were exposed to a breathing resistance (20 $cmH_2O/l/s$ in Study 1; 10 $cmH_2O/l/s$ in Study 2), while a resistance figure was presented. After 40 s, the breathing resistance was removed during the resistance offset phase while the resistance figure disappeared and the offset figure was presented. In this offset figure, one of two operant symbols was presented: a punishment symbol in the punishment blocks or a no punishment symbol in the no punishment blocks.

During the learning blocks, breathing was monitored online by the experimenter. During the no punishment learning block, a sigh during the presentation of the operant symbol was followed by a continued 20-s interval of no resistance after the sigh. During this interval, the operant symbol disappeared while the offset figure remained on the screen indicating no resistance was present. Following this interval, the next trial started. During the punishment learning block, a sigh during the presentation of the other operant symbol was punished by the transition to a 20-s interval during which a resistance was added after the sigh. In Study 1, this resistance was a strong resistance of 40 $cmH_2O/l/s$, indicated by a high resistance figure (while the offset figure and the operant symbol disappeared). After this 20-s resistance interval, a 20-s recovery period was added before the next trial started. In Study 2, this resistance was a very mild resistance of 10 $cmH_2O/l/s$, indicated by the resistance figure (while the offset figure and the operant symbol disappeared), after which the next trial started immediately without recovery period. If participants did not sigh during the resistance offset phase for 20s, the next trial started.

During the test blocks, the 40-s resistance phase (signaled by the resistance figure) was followed by the 20-s offset phase (signaled by an offset figure). During the punishment test block, the operant symbol predicting punishment was presented in the offset figure. During the no punishment test block, the operant symbol predicting no punishment was presented in the offset figure. However, sighs no longer were followed by a punishment or no punishment interval. After the 20-s resistance offset phase, the next trial started.

The order of the punishment and no punishment blocks within the learning and test blocks, and the meaning of figures and symbols was counterbalanced between participants.

Data analysis

Respiratory parameter extraction. The respiratory signals, the self-report data and the stimulus presentation events were synchronized using Matlab R2016a (The MathWorks). Raw respiratory signals were visualized, screened for artefacts and analyzed using Vivosense software (Vivonoetics, Inc.). First, individual proportions of ribcage and abdomen to respiratory volumes were determined by means of a qualitative diagnostic calibration (Sackner et al., 1989). Next, respiratory time and (uncalibrated) volume of each breath were calculated. Sighs within each block were defined as deep breaths, i.e. breaths with an inspiratory volume at least twice as large as the mean inspiratory volume during the respective block (Ramirez, 2014; Vlemincx et al., 2013b; Wilhelm, Trabert, & Roth, 2001b).

Statistical analysis. The number of sighs during each phase of each trial of each block was calculated as a dependent count variable (sigh frequency). To check whether sighs were accurately monitored and consistently punished and not punished, sigh frequency during the offset phases of the learning blocks were compared in a 2 (administration of either no punishment or punishment (yes, no)) x 2 (operant symbol (no punishment, punishment)) design.

To test the learning effect of sighs, sigh frequency was subjected to a Poisson regression with a random intercept (to account for potential differences in sigh frequency between participants). Sigh frequency during the presentation of two operant symbols (no punishment, punishment) during the offset phases of the test blocks were compared. The categorical predictor ‘operant symbol’ was added to the models using dummy-coding. Effects were estimated using the SAS procedure GLIMMIX (SAS 9.2, SAS Institute Inc.). In a Poisson regression, exp(β) can be interpreted as the effect size indicating the ratio at which the dependent variable differs between compared conditions.

To explore learning across trials within learning blocks and extinction of learning across trials within test blocks in the sample, the linear trend in sigh frequency across trials during the presentation of the two operant symbols (no punishment or punishment) during the resistance offset phases of the learning and test blocks was plotted in Figures 2 and 3.

Accordingly, linear trends in sigh frequency across trials were tested in a Poisson regression with a random intercept and phase (learning, test), operant symbol (no punishment, punishment) and trial (1-16) as categorical predictors.

Results

Manipulation check: Were sighs accurately punished and not punished?

Since sighs during the offset of the resistance were online monitored by the experimenter and manually followed by punishment in one learning block and by no punishment in the other learning block, a manipulation check was performed to evaluate whether sighs were accurately detected. In 62% and 64% of the trials in which a sigh was followed by a no punishment interval, an actual sigh occurred in Studies 1 and 2, respectively. In 66% and 69% of the trials in which a sigh was punished, an actual sigh occurred in Studies 1 and 2, respectively. Reversely, in trials during which sighs occurred, sighs were followed by a no punishment interval in 91% and 94% of the trials in Studies 1 and 2, respectively, and sighs were followed by a punishment interval in 87% and 85% of the trials in Studies 1 and 2, respectively. These results indicate that sighs were accurately followed by punishment and no punishment intervals at a rate of 85-94% in both studies.

Can sighs become learned responses?

To test whether sighs can be brought under stimulus control via an operant learning paradigm, sigh frequencies in response to the two different operant symbols (no punishment vs. punishment) during the resistance offset in the test phase were compared (Figure 4). Both Study 1 and Study 2 showed significantly different sigh frequencies in response to no punishment cues compared to punishment cues (Study 1: $F(1,1546)=5.37$, $p=0.0207$; Study 2: $F(1,1274)=8.24$, $p=0.0042$). Results from Study 1 show that sigh frequency was 1.20 times higher during cues that predicted no punishment of a sigh compared to cues that predicted punishment of a sigh (β=0.18, exp(β)=1.20, t(1546)=2.32, p=0.0207). Results from Study 2 show that sigh frequency was 1.28 times higher during cues that predicted no punishment of a sigh compared to cues that predicted punishment of a sigh (β=0.25, exp(β)=1.28, t(1274)=2.87, p=0.0042).

Learning across trials.

In Study 1, the linear trends in sigh frequency across trials during the learning blocks were not significant; the linear trend was negative for the no punishment block (β=-1.36, t(1310)=-0.33, p=0.7410) and positive for the punishment block (β=4.29, t(1310)=0.91, p=0.3652). Also the linear trends in sigh frequency across trials during the test blocks were not significant; the linear trend was negative for the no punishment block (β=-6.35, t(1518)=-1.89, p=0.0585) and positive for the punishment block (β=6.0459, t(1518)=1.49, p=0.1351).

Similarly, in Study 2, non-significant linear trends in sigh frequency across trials during the learning blocks were found; the linear trend was positive for the no punishment block (β=3.06, t(1105)=0.72, p=0.4704) and negative for the punishment block (β=-3.1704, t(1105)=-0.75, p=0.4547). Also the linear trends in sigh frequency across trials during the test blocks were not significant; the linear trend for the no punishment block (β=-1.19, t(1246)=-0.32, p=0.7486) and for the punishment block (β=-2.87, t(1246)=-0.68, p=0.4974) were both negative.

Discussion

The present studies show that sighs can become learned behaviors via operant learning. Sighs evoked by the offset of a respiratory resistance occurred less frequently in contexts in which sighs were punished by the onset of a resistance compared to contexts in which sighs were not punished. These results suggest that potential aversive physiological and psychological effects of sighs may decrease sigh frequency. If operant learning processes influence sigh frequency, conversely, also the positive physiological and psychological effects of sighs may increase sigh frequency. In the current studies, the no punishment interval after a spontaneous sigh consisted of continued dyspnea relief, which could be considered a reward by positive reinforcement (e.g. the addition of a period of non-resistive breathing) or negative reinforcement (e.g. the continued offset of a resistance) in a paradigm in which the default is resistive breathing. That both punishment and reward may have affected sigh frequency is supported by the trends in sigh frequency during the learning phase in Study 2; sigh frequency during learning increased when sighs were followed by dyspnea relief, whereas sigh frequency during learning decreased when sighs were followed by dyspnea punishment. Presumably as a result of this learning process, in the test block, sigh frequency during cues predicting dyspnea punishment after a sigh was lower than sigh frequency during cues predicting continued dyspnea relief after a sigh in Studies 1 and 2. Furthermore, consistent with extinction of learning, sigh frequency decreased across trials during the test block in Study 2.

Although operant learning effects were supported by differences in predicted sigh frequency between punishment and no punishment trials in the test blocks, learning across trials in the learning blocks and extinction across trials in the test blocks, as found in Study 2, were not present in Study 1. This may not be surprising, however, given the paradigm we used in Study 1. In Study 1, the default resistance was higher than in Study 2, and the punishment of a sigh during learning involved a very strong resistance. This may have resulted in opponent processes. On the one hand, sigh frequency was lower in response to dyspnea punishment, i.e. lower than the baseline sigh frequency we observed previously in response to the offset of a resistance of this magnitude (Vlemincx et al., 2018). On the other hand, the need to sigh to relieve may have been higher, especially in the highly resistive punishment blocks, resulting in increases in sigh frequency across punishment learning trials. During the test phase, sigh frequency across trials seemed to return to the previously observed baseline level of sighing in response to the offset of a resistance of this magnitude (Vlemincx et al., 2018), resulting in a decrease in sigh frequency across no punishment test trials, and an increase in sigh frequency across punishment test trials. Altogether, these findings suggest that sigh frequency in both studies is dependent on operant learning processes.

The role of operant learning in sighing behavior has important implications. First, the present results show how learning may be a crucial process determining the frequency of sighs during physiological and psychological regulatory states. For example, the physiological rewarding effects of a sigh, such as the restoration of lung compliance and the recovery of normal levels of oxygen and carbon dioxide, may increase sigh frequency in physiological and psychological states in which lung compliance and gas levels become compromised, such as obstructed breathing or perceived dyspnea, and emotional states of stress and anxiety. Alternatively, the psychological rewarding effects of a sigh, such as relief (Vlemincx, Taelman, et al., 2010; Vlemincx et al., 2016), may increase sigh frequency in psychological states that require regulation, such as stressful, emotional and symptom-inducing contexts. Accordingly, increased sigh frequencies have been found during mental arithmetic stress (Vlemincx, Taelman, De Peuter, Van Diest, & Van Den Bergh, 2011b; Vlemincx, Van Diest, & Van den Bergh, 2012) and negative and high arousal emotional states (Vlemincx, Van Diest, & Van den Bergh, 2015), such as aggression (Carnevali, Nalivaiko, & Sgoifo, 2014), joy and depression (Vlemincx et al., 2015), and fear and anxiety (Blechert, Michael, Grossman, Lajtman, & Wilhelm, 2007; Carnevali et al., 2013; Studer et al., 2012; Studer, Danuser, Wild, Hildebrandt, & Gomez, 2014; Tobin et al., 1983; Vlemincx et al., 2015). For example, during mental arithmetic, sigh frequency was significantly associated with resilience and habituation to stress (Walker et al., 2019). Thus, sighs can be adaptive behaviors in response to stress and emotions.

Furthermore, these learning processes may explain how sighs can become maladaptive behaviors, as is the case in the excessive sighing behavior in panic disorder patients. If panic disorder patients experience anxiety in situations they perceive as threatening, a sigh may momentarily reduce their anxiety and temporarily induce physiological and psychological relaxation and relief. These relieving effects of a sigh may reinforce sighing in situations perceived as threatening by panic disorder patients, even though physiologically a threat response may not be warranted. Given that the threat sensitivity of panic disorder patients is high, they may sigh so frequently that, on the long term, respiration exceeds metabolic need, causing hyperventilation and respiratory dysregulation.

Showing the importance of learning processes in sighing behavior, these findings have important clinical implications. These findings suggest that learning may be a key mechanism in adaptive sighing, and conversely in maladaptive sighing contributing to respiratory dysregulation and symptoms. Additionally, these findings also suggest how learning processes may be used to create awareness of the physiological and psychological effects of sighing and how operant learning can be a means to modify and optimize adaptive sigh patterns. For example, operant learning can be used as a tool to decrease sigh frequency in persons who are sighing excessively. So far, treatment to remediate respiratory dysregulation in panic disorder patients effectively focuses on carbon dioxide biofeedback and instructions of slow and regular breathing (Meuret et al., 2008). An alternative method focusing on sighs specifically, may consist of the contextual learning of sighs, e.g. during exposure therapy, to train panic disorder patients in which contexts sighs are beneficial by rewarding sighs, and in which contexts sighs are dysregulating by punishing sighs. Similarly, conditioning of sighs can be incorporated in exposure therapy for patients with respiratory or cardiovascular disease to manage dyspnea, and in breathing training for stress reduction and emotion regulation.

Despite the significant contributions of this study to our understanding of the mechanisms of sighing, some limitations need to be acknowledged. First, the present study can conclude that learning mechanisms may play a role in sigh frequency, yet cannot firmly distinguish whether punishment or reward effects are underlying the present findings. Future studies could investigate whether sigh frequency increases due to reward of sighs in the absence of punishment and/or whether sigh frequency decreases due to punishment of sighs in the absence of reward. Second, the present learning effects of sighs are limited to sighs elicited by the offset of a respiratory resistance or dyspnea relief. Whether sighs elicited by other triggers, such as stress or anxiety, are subject to learning processes, should be further investigated. Third, punishment and reward of sighs in this study are restricted to respiratory stimuli inducing dyspnea and dyspnea relief. Despite respiratory punishment and reward being directly relevant to the established physiological and psychological effects of sighs, and thus being a strength of this study, it remains to be investigated whether punishment and reward outside the respiratory system can induce the same learning effects. Fourth, although sigh frequencies in both studies are consistent with sigh frequencies we previously reported in response to the offset of the resistances used in the current studies, next studies could include a baseline assessment of sigh frequency.

In summary, the present studies show that sighs can become learned behaviors. Understanding learning processes in the respiratory system is crucial in disentangling the mechanisms underlying stress and emotion induced breathing patterns, and essential in unravelling the mechanisms underlying respiratory dysregulation in anxiety disorders, and panic disorder specifically.

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Disclosures

EV and OL report no potential conflicts of interest.

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Figure captions

Figure 1. Graphical representation of the design of Study 1 and 2. Each trial started with the presentation of a resistance. In a next phase, the resistance offset phase, the resistance was removed and an operant symbol was presented that predicted either no punishment or punishment of a sigh during the resistance offset. Sighs were monitored online. A spontaneously occurring sigh during the resistance offset phase was followed by the continued resistance offset during the subsequent phase in learning no punishment blocks. A spontaneously occurring sigh during the resistance offset phase was punished by the onset of a resistance offset during the subsequent phase in learning punishment blocks. During test blocks, sigh rate was compared during symbols predicting no punishment of a sigh versus symbols predicting punishment of a sigh.

Figure 2. Trend in sigh frequency across trials during operant symbols associated with no punishment and punishment of sighs during the learning and test blocks in Study 1.

Figure 3. Trend in sigh frequency across trials during operant symbols associated with no punishment and punishment of sighs during the learning and test blocks in Study 2.

Figure 4. Predicted (bar) and observed (*) sigh frequency in response to operant symbols associated with the no punishment and punishment of sighs during the test blocks in Studies 1 and 2. Error bars denote 95% confidence intervals.

Figure 1

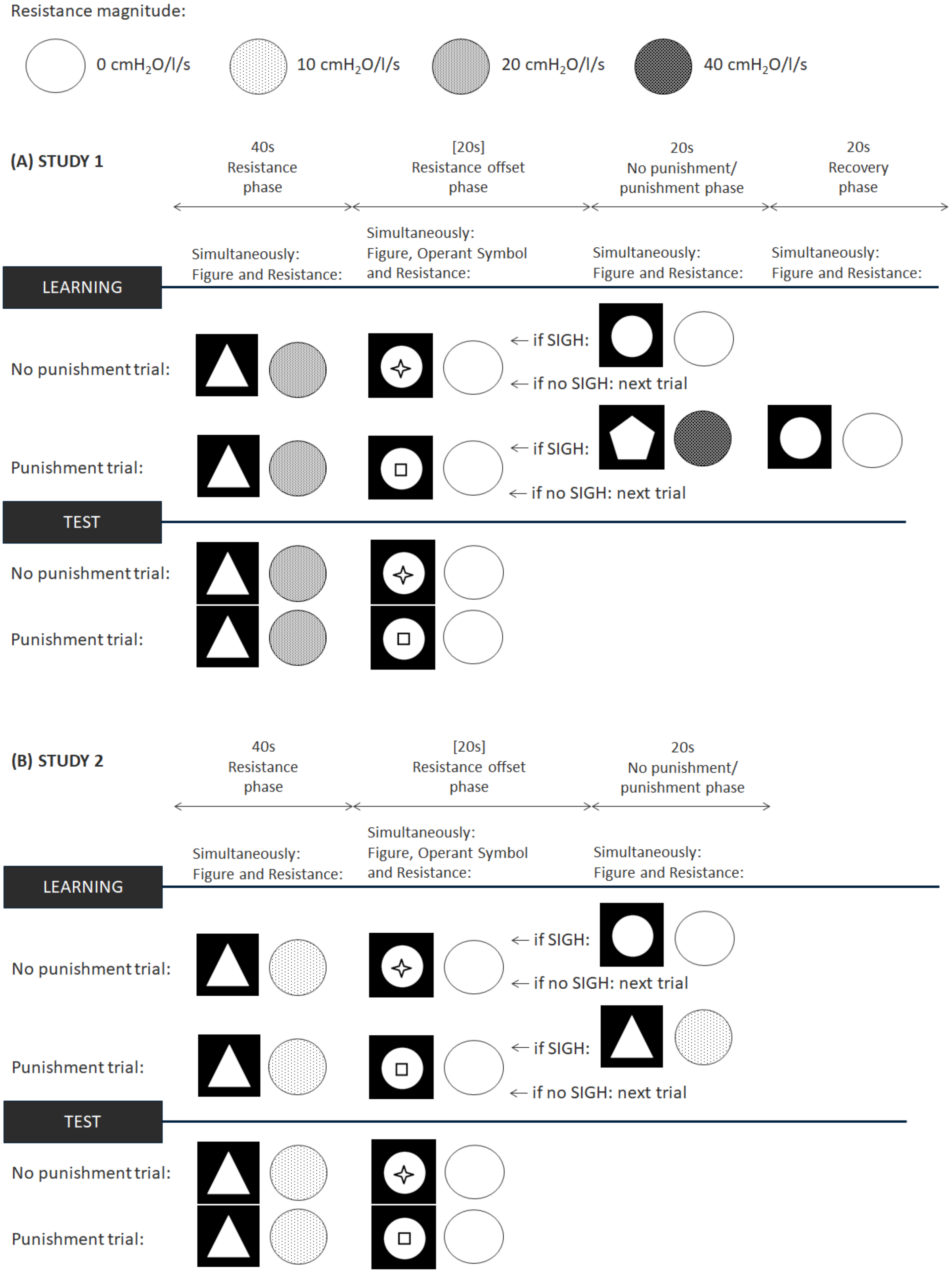

Resistance magnitude:
0 cmH2O/l/s
10 cmH2O/l/s
20 cmH2O/l/s
40 cmH2O/l/s
(A) STUDY 1
40s
Resistance
phase
[20s]
Resistance offset
phase
20s
No punishment/
punishment phase
20s
Recovery
phase
Simultaneously:
Figure and Resistance:
Simultaneously:
Figure, Operant Symbol
and Resistance:
Simultaneously:
Figure and Resistance:
Simultaneously:
Figure and Resistance:
LEARNING
No punishment trial:
if SIGH:
if no SIGH: next trial
Punishment trial:
if SIGH:
if no SIGH: next trial
TEST
No punishment trial:
Punishment trial:
(B) STUDY 2
40s
Resistance
phase
[20s]
Resistance offset
phase
20s
No punishment/
punishment phase
Simultaneously:
Figure and Resistance:
Simultaneously:
Figure, Operant Symbol
and Resistance:
Simultaneously:
Figure and Resistance:
LEARNING
No punishment trial:
if SIGH:
if no SIGH: next trial
Punishment trial:
if SIGH:
if no SIGH: next trial
TEST
No punishment trial:
Punishment trial:

Figure 2

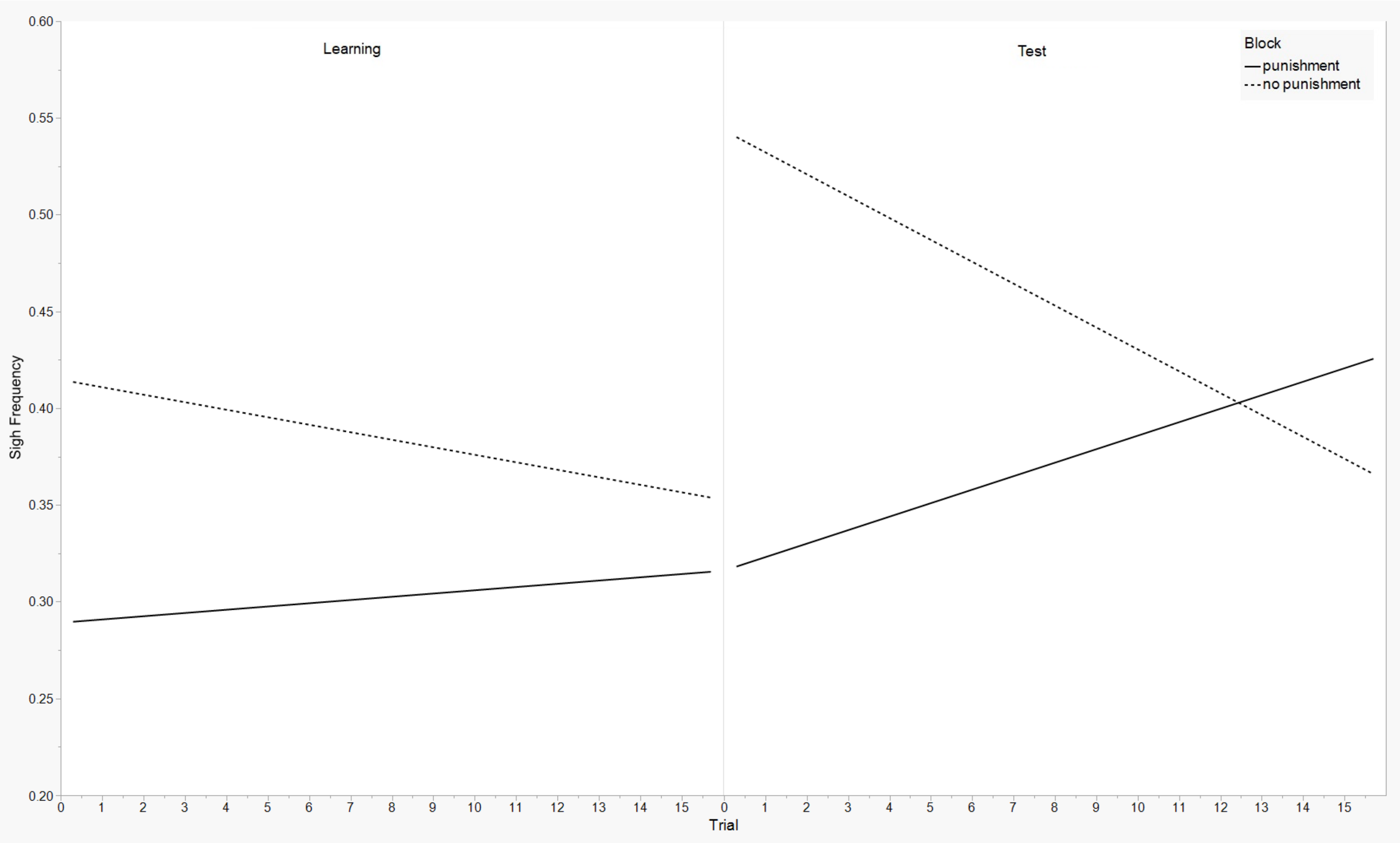

Learning
Test
Block
punishment
no punishment
Sigh Frequency
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Trial

Figure 3

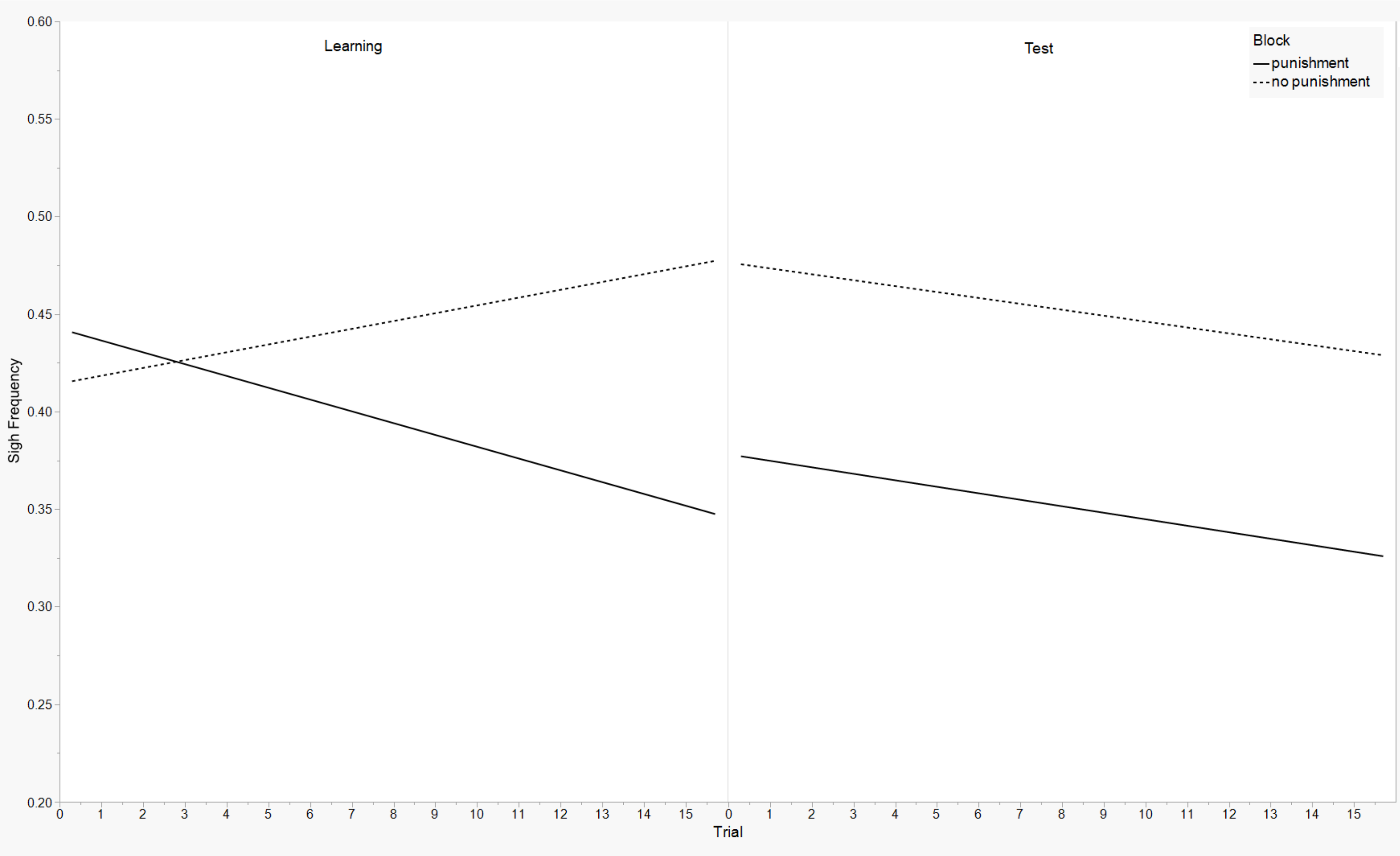
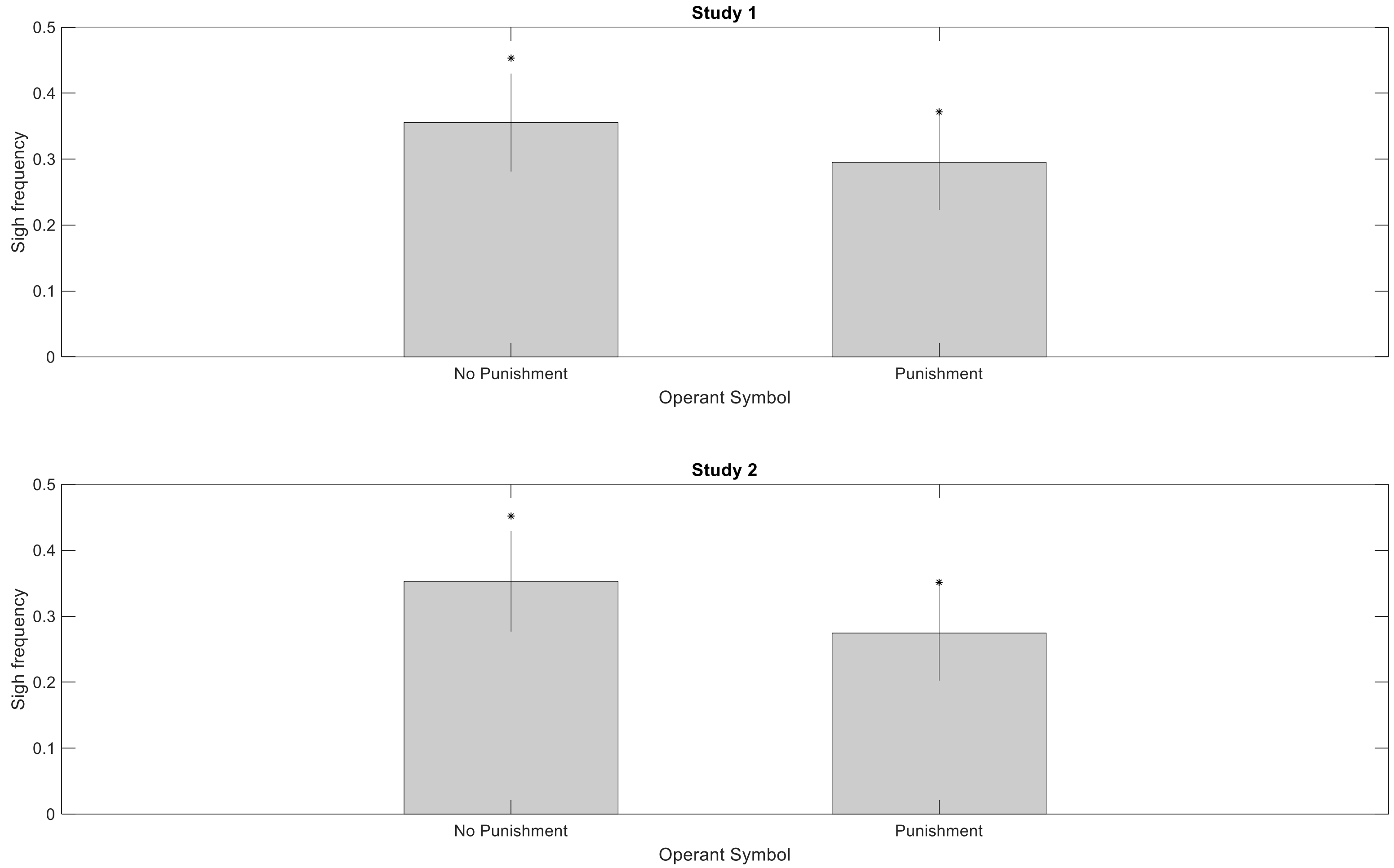

Learning
Test
Block
punishment
no punishment
Sigh Frequency
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Trial

Figure 4


Study 1
0.5
0.4
0.3
0.2
0.1
0
Sigh frequency
*
*
No Punishment
Punishment
Operant Symbol
Study 2
0.5
0.4
0.3
0.2
0.1
0
Sigh frequency
*
*
No Punishment
Punishment
Operant Symbol