

Review

The role of the striatum in aversive learning and aversive prediction errors

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Neural systems that support learning from punishment are distinct from those that support learning from reward. However, the role of the striatum in aversive learning and aversive prediction errors (PE) is unclear. We used a task that required learning about the magnitude of punishment (PE) to test the role of the striatum in aversive learning. The results show that the striatum is involved in learning about the magnitude of punishment (PE) and that the striatum is also involved in learning about the magnitude of punishment (PE).

Keywords: aversive learning; aversive prediction errors; striatum; punishment; learning

1. INTRODUCTION

The striatum is a key component of the basal ganglia and is involved in a wide range of functions, including motor control, cognition, and emotion. The striatum is also involved in learning, particularly in learning about the magnitude of punishment (PE). The striatum is involved in learning about the magnitude of punishment (PE) and that the striatum is also involved in learning about the magnitude of punishment (PE).

It is clear that the striatum is involved in learning about the magnitude of punishment (PE) and that the striatum is also involved in learning about the magnitude of punishment (PE). The results show that the striatum is involved in learning about the magnitude of punishment (PE) and that the striatum is also involved in learning about the magnitude of punishment (PE).

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2008). The striatum is involved in learning about the magnitude of punishment (PE) and that the striatum is also involved in learning about the magnitude of punishment (PE). The results show that the striatum is involved in learning about the magnitude of punishment (PE) and that the striatum is also involved in learning about the magnitude of punishment (PE).

A key component of the basal ganglia is the striatum, which is involved in a wide range of functions, including motor control, cognition, and emotion. The striatum is also involved in learning, particularly in learning about the magnitude of punishment (PE). The results show that the striatum is involved in learning about the magnitude of punishment (PE) and that the striatum is also involved in learning about the magnitude of punishment (PE).

... W... PE
...
(S... et al. ...)
...
(P... et al. 2004).

(a) Amygdala contributions to affective learning

I... (CS), ...
... (US). A...
... (CR). S...
... (L.D. 2000; M... 2001).
U... A...
... T... CS...
US... (R... et al. 1993). L... LA...
CS US... (W... et al. 1999; D... et al. 2006). T... LA...
... (CE) ... (P... et al. 1995; P... et al. 1997. pp. 238-279) EP 2(r. T 1 T 4.633 8696D ()-450.3()TJ/F4 1 T 1.8893786

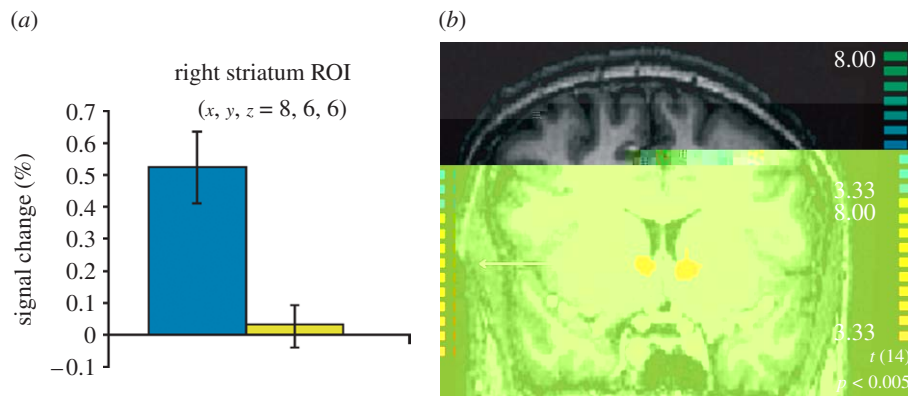


Figure 1. (a,b) Striatal signal change in response to CS+ and CS- in the right striatum ROI. ROI, region of interest; CS+, conditioned stimulus; CS-, unconditioned stimulus. (a) Signal change in the right striatum ROI (x, y, z = 8, 6, 6) in response to CS+ (blue bar) and CS- (yellow bar). Error bars represent standard error of the mean. (b) Axial MRI scan showing the location of the ROI in the striatum. The color scale indicates the t-value for the ROI, with a significance level of $t(14) < 0.005$.

(i) Appetitive conditioning in the striatum

Numerous studies have shown that the striatum is involved in appetitive conditioning (Sutton et al. 1997). Appetitive conditioning involves learning about the relationship between a stimulus (US) and a reward (DA). The striatum is involved in the processing of DA signals, which are used to update the value of the stimulus (Sutton et al. 1997). The striatum is also involved in the processing of DA signals, which are used to update the value of the stimulus (Sutton et al. 1997). The striatum is also involved in the processing of DA signals, which are used to update the value of the stimulus (Sutton et al. 1997).

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ROI (ROI) (O'Driscoll et al. 2001). I (Sutton & Barto 1998). A (O'Driscoll 2004), (Elliott et al. 2004; O'Driscoll 2004; Taylor et al. 2004), (Dolan et al. 2005).

() *Temporal difference learning in the striatum*

C (TD) (Sutton & Barto 1990) (Maddox et al. 1996; Sutton et al. 1997).

T PE (Sutton & Barto 1990) PE PE W PE T

I PE (TD) PE PE

(Herrnstein et al. 1994). H PE PE S TD

(MCClelland et al. 2003; O'Driscoll et al. 2003; Sutton et al. 2007; Taylor et al. 2007). T (BOLD) (O'Driscoll et al. 2003) (MCClelland et al. 2003) PE

I (Nairn et al. 2003). PE

(O'Driscoll 2004). I PE (Sutton et al. 2007), (Herrnstein et al. 2008). F PE (Barto & O'Driscoll 2007), (Koeber et al. 2005).

A DA PE (fMRI) T BOLD (Larsen et al. 2001). N MRI

PE (D'Armentano et al. 2008). T BOLD PE I PE

() *Aversive processing and the striatum*

E (Sutton (1994), Herrnstein (2000), D'Armentano (2002), W & S (2003), P & F (2004), M N & W (2006) S et al. (2007)). A DA

I DA (Merrill & S 1996; U et al. 2004). H DA NA (R et al. 1987; A et al. 1989; M C & S 1992; K & D 1995; T & M 1996; 2004), CS (et al.

1993, 1998; S & M 1995b; W 1997; M et al. 2000; P et al. 2001, 2002; J et al. 2004; & 2004). DA

NA (Carr et al. 1974; Nair et al. 1974; J. et al. 1977; S. & C. 1985; W. et al. 1990; M. C. et al. 1993; L. et al. 2004). T. DA, DA. DA, DA. I. (M. et al. 1980; & H. 1990; F. & T. 2007; G. & T. 2007). L. NA. NA (R. et al. 1997; W. et al. 1997; H. & W. 1999; P. et al. 1999; L. et al. 2002; J.-R. et al. 2003; S. & S. 2003; J. et al. 2004). T. NA. A. (W. & H. 1990; D. & C. 1992; & B. 1992; J.-R. et al. 1993; K. et al. 1997; P. et al. 1999, 2000; P. et al. 2001, 2002; P. & F. 2004). I. S. (W. & M. 1969; A. & D. 1973; W. 1974; P.-A. et al. 1975; V. & W. 1989; W. & V. 1991; W. & S. 2003). C. fMRI. A. US. (B. et al. 1998, 1999; L. B. et al. 1998; W. et al. 1998; P. et al. 2004; S. et al. 2005). S. (P. et al. 2000; S. et al. 2005). (D. 2007; S. et al. 2007; T. et al. 2007). T. (B. et al. 2001). (J. et al. 2003). A. (L. et al.) fMRI. H.

(B. et al. 2001; G. et al. 2002; et al. 2006), (K. et al. 2001a). (.) PE and striatum during aversive processing I. PE. H., PE. F., PE. O. PE. (D. et al. 2002). H., PE. (P. et al. 2006). (M. et al. 2007). C. DA. (et al. 1993, 1998; S. & M. 1995a; W. 1997; M. et al. 2000; P. et al. 2001, 2002; J. et al. 2004; 2004). T. DA. PE. A. PE. C. fMRI. PE. (S. et al. 2005, 2007; K. et al. 2006; T. et al. 2007), (S. et al. 2007). H. (K. et al. 2006), PE. BOLD. ? S. PE. (PE). BOLD. (M. C. et al. 2003; O'D. et al. 2003; S. et al. 2007; T. et al. 2007). I. A., PE. A. PE. I. BOLD. PE. PE. (J. et al. 2003; S. et al. 2004, 2005, 2007). F., S. et al. (2004). BOLD.

A

(...). We ... CS+, ... CS-, ... M ... PE ... PE+ ... (T ... : $x, y, z = -7, 3, 9$; ... : $x, y, z = 9, 5, 8$).

I ... PE ... TD ... PE

2. GENERAL METHODS

(a) *Participants*

F ... A ... 14 ... 3 ... T ... U ... C ... A ... I ... H ... S

(b) *Procedure*

T ... (... 2): ... D ... *et al.* 2000) ... D ... *et al.* 2006). T ... I ... 5 (... 2a). D ... 2 ... MRI ... 50/50

T ... (6, 7, 8, 9) ... (1, 2, 3, 4) ... 5. T ... 500 ... 500 ... 13 ... A ... \$4.00 ... -\$2.00 ... 5' ... 16 ... 18 ... 21 ... 21 ... 12 ... U ... 50 ... A ... \$42.00

I ... (... 2b). T ... : CS) ... 4, ... 12

\$24.00. T
\$60.00

(c) Physiological set-up, assessment and behavioural analysis

S (SCR) BIOPAC
S A A C
RF
ACQKNOWLEDGE
SCR T SCR
0.5 4.5
CS, (L Br et al. 1995).
A 0.02 μS
0. T
(L Br et al. 1998). A SCR
T
CS+ \$4.00
CS+
US SCR CS+
T - t-
CS+ CS-

(d) fMRI acquisition and analysis

A 3T S A
S N U C B I
A T1-
(256×256, 176 1-).
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2000, TE=20, FOV=192, =
75°, =4340 H
=0.29). T
(3×3×3). AC PC
A
BRAIN VO AGER (B I,
M, T N). T
(
), Fr G (4
FWHM),
(
). Sr T
(T & T 1988).
A (GLM)
11 T 12 3
CS (CS-, CS+ CS+-US;
US); 2 US (US N US);
1 PE; 6
x, y, z. T
(PE)
p<0.001
10

T PE TD
TD
(S et al.). I TD
V(t) t
w_i
x_i(t) 1
(CS) t, 0
V̂(t) = ∑ w_i x_i(t). (2.1)

A
t
t+1 t, PE,
δ(t) = r(t) + γV̂(t+1) - V̂(t), (2.2)

r(t) t. I
D γ
U, γ
0<γ<1. I
0.99. T
B,
w_i ← w_i + λ ∑ x_i(t) δ(t), (2.3)

λ 0.2
W CS
CS 0.4 W (λ=
0.2, γ=0.99 w_i=0.4), PE
(2.1) (2.2)
fMRI

3. RESULTS

(a) Physiological assessment of aversive conditioning

A SCR
(3). T SCR CS+
(M=0.33, =0.25)
CS- (M=0.15, =0.07)
(t(13)=3.48, p<0.005). C-
CR (CS+ CS-)
1 2 (t(12)=1.53, p=0.15) 1 3
(t(12)=0.97, p=0.35)
3. F,
CS+ CS-
(t(10)=5.49, p<0.0005).

(b) Neuroimaging results

T
PE A
PE
(p<0.001,
10). T

Table 1. PE parameters for each subject.

Subject	Condition	Tuning parameters			Number of trials
		x	y	z	
Subject 1	BA 9/24	24	10	35	337
Subject 2	BA 24/32	-13	37	14	869
Subject 3	BA 24/32	16	30	8	280
Subject 4	BA 24/32	13	20	4	329
Subject 5	BA 24/32	6	-24	4	334
Subject 6	BA 41/21	-40	-31	2	524

of the subjects (range = 1), indicating that the model fits the data well. The mean correlation between the model and the data was 0.94. The mean correlation between the model and the data was 0.94. The mean correlation between the model and the data was 0.94.

4. DISCUSSION

The present study shows that the human striatum is involved in learning from punishment. We used a task that required subjects to learn to avoid a punishment. The results show that the striatum is involved in learning from punishment. The results show that the striatum is involved in learning from punishment. The results show that the striatum is involved in learning from punishment.

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... P. & L. D. (2005) ... (A. et al. 2003). T. ... Fr., ... PE. Fr. ... N. H. A. N. T. A. I. H. S. T. S. F. N. U. C. B. I. J. S. M. D. F. E.A.P.T. C. L.

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