Network Dynamics are Associated with Reinforcement Learning

Models

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Behavioral Learning Model

We ran a generalized mixed effects logit model predicting proportion correct with block. Subjects demonstrated significant learning across the task.

```
## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: binomial  ( logit )
## Formula: correct ~ block_int + (block_int | subject)
##    Data: flex_behav
## Weights: weights
##
##      AIC      BIC   logLik deviance df.resid
##    468.1    480.5   -229.1    458.1       83
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -1.6088 -0.4340  0.1505  0.5624  1.6471
##
## Random effects:
##  Groups  Name        Variance Std.Dev. Corr
##  subject (Intercept) 1.0237   1.0118
##          block_int   0.2195   0.4685   0.81
## Number of obs: 88, groups:  subject, 22
##
## Fixed effects:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)   1.1864     0.2250   5.272 1.35e-07 ***
## block_int     0.2820     0.1136   2.482   0.0131 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##           (Intr)
## block_int 0.748
```

Effect of Flexibility on Reinforcement Learning

Striatal flexibility- REML

We fit a mixed effects generalized linear model using a REML approximation to associate individual learning performance with striatal flexibility across blocks, using lme4.

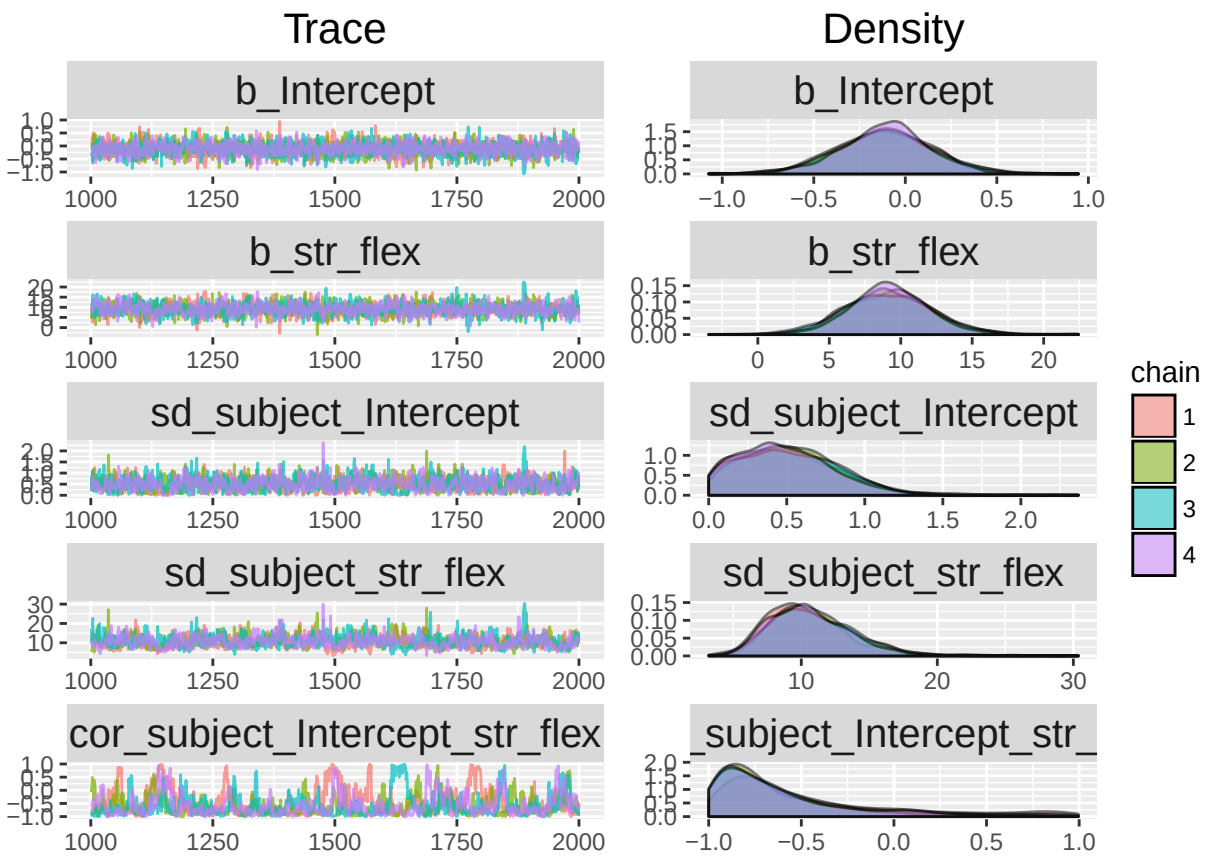
```
## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: binomial  ( logit )
## Formula: correct ~ str_flex + (str_flex || subject)
##    Data: flex_behav
## Weights: weights
##
##      AIC      BIC   logLik deviance df.resid
##    494.8    504.7   -243.4    486.8       84
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.63858 -0.73581 -0.02002  0.85468  2.43378
##
## Random effects:
##  Groups    Name        Variance  Std.Dev.
##  subject   (Intercept) 2.796e-08 0.0001672
##  subject.1 str_flex    6.196e+01 7.8715162
## Number of obs: 88, groups:  subject, 22
##
## Fixed effects:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  0.04581    0.23683   0.193  0.84662
## str_flex     9.45132    2.74667   3.441  0.00058 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##          (Intr)
## str_flex -0.772

## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: binomial  ( logit )
## Formula: correct ~ str_flex + str_flex_mean + (str_flex || subject)
##    Data: flex_behav
## Weights: weights
##
##      AIC      BIC   logLik deviance df.resid
##    496.3    508.6   -243.1    486.3       83
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.52483 -0.74572 -0.05168  0.81802  2.43855
##
## Random effects:
##  Groups    Name        Variance Std.Dev.
##  subject   (Intercept)  0.00    0.000
##  subject.1 str_flex    66.28    8.141
## Number of obs: 88, groups:  subject, 22
##
## Fixed effects:
##               Estimate Std. Error z value Pr(>|z|)
## (Intercept)      1.236      1.671   0.740 0.459478
```

```
## str_flex         9.792      2.819   3.473 0.000514 ***
## str_flex_mean  -11.137     15.454  -0.721 0.471150
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) str_fl
## str_flex     0.053
## str_flex_mn -0.990 -0.162
```

Striatal flexibility- Bayesian model

For appropriate posterior inference, we fit the same model using Hamiltonian Monte Carlo to generate a full posterior distribution for the effect of striatal flexibility on learning performance. We used the 'brms' package to build Stan models.

```
##  Family: binomial (logit)
## Formula: numcorr ~ str_flex + (str_flex | subject)
##    Data: flex_behav (Number of observations: 88)
## Samples: 4 chains, each with iter = 2000; warmup = 1000; thin = 1;
##          total post-warmup samples = 4000
##    WAIC: Not computed
##
## Random Effects:
## ~subject (Number of levels: 22)
##                           Estimate Est.Error l-95% CI u-95% CI Eff.Sample
## sd(Intercept)                 0.51      0.31     0.03     1.15        929
## sd(str_flex)                 10.69      3.08     5.99    17.27        460
## cor(Intercept,str_flex)      -0.56      0.43    -0.98     0.73        195
##                           Rhat
## sd(Intercept)             1.00
## sd(str_flex)              1.01
## cor(Intercept,str_flex) 1.02
##
## Fixed Effects:
##           Estimate Est.Error l-95% CI u-95% CI Eff.Sample Rhat
## Intercept    -0.11      0.26    -0.62     0.39       4000    1
## str_flex      9.17      2.96     3.40    15.21       1699    1
##
## Samples were drawn using sampling(NUTS). For each parameter, Eff.Sample
## is a crude measure of effective sample size, and Rhat is the potential
## scale reduction factor on split chains (at convergence, Rhat = 1).
```



Whole-brain flexibility

Because a global measure of flexibility has also been shown to relate to a number of cogitive processes (Bassett et al 2011, Braun et al 2015), we fit another mixed-effects model with this whole-brain metric as a predictor.

```
## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: binomial  ( logit )
## Formula: correct ~ wb_flex + (wb_flex || subject)
##    Data: flex_behav
## Weights: weights
##
##      AIC      BIC   logLik deviance df.resid
##    511.5    521.4   -251.8    503.5       84
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.67954 -0.71005 -0.01157  0.81079  2.72652
##
## Random effects:
##  Groups    Name        Variance Std.Dev.
##  subject   (Intercept)  0.00    0.000
##  subject.1 wb_flex     64.94    8.058
## Number of obs: 88, groups:  subject, 22
##
```

```
## Fixed effects:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  -0.1104     0.3506  -0.315  0.75287
## wb_flex      11.8486     3.9126   3.028  0.00246 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##         (Intr)
## wb_flex -0.889
```