

Reeves et al 2023: Analysis Script

Bayesian Models

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This markdown document accompanies the paper entitled, “Simulation and social network analysis provide insight into the acquisition of tool behavior in hybrid macaques”.

This script can be used to analyze the data used to generate figures 2 and 3 in the text. The data can be downloaded from the Dryad repository associated with the paper.

Load required packages

User defined variables

```
N_CHAINS <- 3
```

Formal Specification of the Model

```
model_spec <- alist(  
  U ~ dbinom(1, p),  
  logit(p) <- a[H] + bC[H] * C + bS[H] * S,  
  a[H] ~ dnorm(0,1.5),  
  bC[H] ~ dlnorm(0,.3),  
  bS[H] ~ dlnorm(0,.3)  
)
```

Create a place to keep all the model results for plotting later.

```
models <- list()
```

Analysis of ABM data

ABM: Social Learning Condition

```
set.seed(11) # The seed is set for consistent outcomes
nodes <- read.csv("../Data/ABM_Social_Condition.csv")
```

```
dat <- list(
  U = nodes$U, # Tool user
  C = nodes$C, # EV centrality
  S = nodes$S, # Strength to tool user
  A = nodes$A, # Age
  H = nodes$H # Phenotype
)
```

```
models$social <- ulam(
  model_spec,
  data = dat,
  chains = N_CHAINS,
  cores = 3,
  iter = 2000,
  log_lik = TRUE,
  cmdstan = TRUE
)
```

```
## Running MCMC with 3 parallel chains, with 1 thread(s) per chain...
```

```
##
```

```
## Chain 1 Iteration:    1 / 2000 [ 0%]  (Warmup)
```

```
## Chain 1 Informational Message: The current Metropolis proposal is about to be rejected because of the
```

```
## Chain 1 Exception: binomial_lpmf: Probability parameter[110] is nan, but must be in the interval [0,
```

```
## Chain 1 If this warning occurs sporadically, such as for highly constrained variable types like covariance
```

```
## Chain 1 but if this warning occurs often then your model may be either severely ill-conditioned or misspecified
```

```
## Chain 1
```

```
## Chain 2 Iteration:    1 / 2000 [ 0%]  (Warmup)
```

```
## Chain 2 Informational Message: The current Metropolis proposal is about to be rejected because of the
```

```
## Chain 2 Exception: binomial_lpmf: Probability parameter[255] is nan, but must be in the interval [0,
```

```
## Chain 2 If this warning occurs sporadically, such as for highly constrained variable types like covariance
```

```
## Chain 2 but if this warning occurs often then your model may be either severely ill-conditioned or misspecified
```

```
## Chain 2
```

```

## Chain 3 Iteration:    1 / 2000 [  0%] (Warmup)
## Chain 3 Iteration:   100 / 2000 [  5%] (Warmup)
## Chain 1 Iteration:   100 / 2000 [  5%] (Warmup)
## Chain 2 Iteration:   100 / 2000 [  5%] (Warmup)
## Chain 1 Iteration:   200 / 2000 [ 10%] (Warmup)
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## Chain 2 Iteration:   200 / 2000 [ 10%] (Warmup)
## Chain 3 Iteration:   300 / 2000 [ 15%] (Warmup)
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## Chain 1 Iteration:   400 / 2000 [ 20%] (Warmup)
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## Chain 3 Iteration:   900 / 2000 [ 45%] (Warmup)
## Chain 1 Iteration:  1000 / 2000 [ 50%] (Warmup)
## Chain 1 Iteration:  1001 / 2000 [ 50%] (Sampling)
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## Chain 3 Iteration:  1400 / 2000 [ 70%] (Sampling)
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## Chain 3 Iteration:  1500 / 2000 [ 75%] (Sampling)
## Chain 2 Iteration:  1500 / 2000 [ 75%] (Sampling)
## Chain 1 Iteration:  1600 / 2000 [ 80%] (Sampling)
## Chain 3 Iteration:  1600 / 2000 [ 80%] (Sampling)
## Chain 2 Iteration:  1600 / 2000 [ 80%] (Sampling)
## Chain 1 Iteration:  1700 / 2000 [ 85%] (Sampling)
## Chain 3 Iteration:  1700 / 2000 [ 85%] (Sampling)

```

```
## Chain 2 Iteration: 1700 / 2000 [ 85%] (Sampling)
## Chain 1 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 3 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 2 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 1 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 3 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 2 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 1 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 1 finished in 17.1 seconds.
## Chain 3 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 3 finished in 17.4 seconds.
## Chain 2 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 2 finished in 17.5 seconds.
##
## All 3 chains finished successfully.
## Mean chain execution time: 17.3 seconds.
## Total execution time: 17.6 seconds.
```

```
xres <- precis(models$social, depth = 2)
xres_link <- apply(xres[,c(1:4)], 2, inv_logit)

xres_link <- cbind(xres_link, xres[c("n_eff", "Rhat4")])
xres_link$n_eff <- round(xres_link$n_eff)
xres_link$Rhat4 <- round(xres_link$Rhat4, 2)
write.csv(xres_link, "../Tables/csvs/social_precis_link.csv")
```

ABM: Inheritance Model

```
set.seed(11)

nodes <- read.csv("../Data/ABM_Inheritance_Condition.csv")

dat <- list(
  U = nodes$U,
  C = nodes$C,
  S = nodes$S,
  A = nodes$A,
  H = nodes$H
)

models$inheritance <- ulam(
  model_spec,
  data = dat,
  chains = N_CHAINS,
  cores = N_CHAINS,
  iter = 2000,
  log_lik = TRUE,
  cmdstan = TRUE)

## Running MCMC with 3 parallel chains, with 1 thread(s) per chain...
##
## Chain 1 Iteration:    1 / 2000 [ 0%] (Warmup)
```

```

## Chain 1 Informational Message: The current Metropolis proposal is about to be rejected because of the
## Chain 1 Exception: binomial_lpmf: Probability parameter[25] is nan, but must be in the interval [0, 1]
## Chain 1 If this warning occurs sporadically, such as for highly constrained variable types like covariance
## Chain 1 but if this warning occurs often then your model may be either severely ill-conditioned or misspecified
## Chain 1

## Chain 2 Iteration:      1 / 2000 [  0%] (Warmup)

## Chain 2 Informational Message: The current Metropolis proposal is about to be rejected because of the
## Chain 2 Exception: binomial_lpmf: Probability parameter[25] is nan, but must be in the interval [0, 1]
## Chain 2 If this warning occurs sporadically, such as for highly constrained variable types like covariance
## Chain 2 but if this warning occurs often then your model may be either severely ill-conditioned or misspecified
## Chain 2

## Chain 3 Iteration:      1 / 2000 [  0%] (Warmup)
## Chain 1 Iteration:    100 / 2000 [  5%] (Warmup)
## Chain 2 Iteration:    100 / 2000 [  5%] (Warmup)
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## Chain 2 Iteration:    200 / 2000 [ 10%] (Warmup)
## Chain 3 Iteration:    200 / 2000 [ 10%] (Warmup)
## Chain 1 Iteration:    200 / 2000 [ 10%] (Warmup)
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## Chain 3 Iteration:    900 / 2000 [ 45%] (Warmup)
## Chain 1 Iteration:    900 / 2000 [ 45%] (Warmup)
## Chain 2 Iteration:   1000 / 2000 [ 50%] (Warmup)

```

```

## Chain 2 Iteration: 1001 / 2000 [ 50%] (Sampling)
## Chain 3 Iteration: 1000 / 2000 [ 50%] (Warmup)
## Chain 3 Iteration: 1001 / 2000 [ 50%] (Sampling)
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## Chain 2 Iteration: 1100 / 2000 [ 55%] (Sampling)
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## Chain 2 Iteration: 1400 / 2000 [ 70%] (Sampling)
## Chain 3 Iteration: 1400 / 2000 [ 70%] (Sampling)
## Chain 1 Iteration: 1400 / 2000 [ 70%] (Sampling)
## Chain 2 Iteration: 1500 / 2000 [ 75%] (Sampling)
## Chain 3 Iteration: 1500 / 2000 [ 75%] (Sampling)
## Chain 1 Iteration: 1500 / 2000 [ 75%] (Sampling)
## Chain 2 Iteration: 1600 / 2000 [ 80%] (Sampling)
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## Chain 2 Iteration: 1700 / 2000 [ 85%] (Sampling)
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## Chain 3 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 1 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 1 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 2 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 3 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 2 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 3 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 2 finished in 11.3 seconds.
## Chain 1 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 1 finished in 11.4 seconds.
## Chain 3 finished in 11.3 seconds.
##
## All 3 chains finished successfully.
## Mean chain execution time: 11.3 seconds.
## Total execution time: 11.5 seconds.

```

```

xres <- precis(models$inheritance, depth = 2)
xres_link <- apply(xres[,c(1:4)], 2, inv_logit)

xres_link <- cbind(xres_link, xres[c("n_eff", "Rhat4")])
xres_link$n_eff <- round(xres_link$n_eff)
xres_link$Rhat4 <- round(xres_link$Rhat4, 2)
write.csv(xres_link, "../Tables/csvs/inheritance_precis_link.csv")

```

Koram Data

Run Model

```
nodes <- read.csv('../Data/Koram.csv')

set.seed(11)

dat <- list(
  U = nodes$U,
  C = nodes$C,
  S = nodes$S,
  A = nodes$A,
  H = nodes$H
)

models$koram_edge <- ulam(
  model_spec,
  data = dat,
  chains = N_CHAINS,
  cores = 10,
  iter = 2000,
  log_lik = TRUE,
  cmdstan = TRUE
)
```

```
## Running MCMC with 3 chains, at most 10 in parallel, with 1 thread(s) per chain...
##
```

```
## Chain 1 Iteration:    1 / 2000 [  0%] (Warmup)
## Chain 1 Iteration:   100 / 2000 [  5%] (Warmup)
## Chain 1 Iteration:   200 / 2000 [ 10%] (Warmup)
## Chain 1 Iteration:   300 / 2000 [ 15%] (Warmup)
## Chain 1 Iteration:   400 / 2000 [ 20%] (Warmup)
## Chain 1 Iteration:   500 / 2000 [ 25%] (Warmup)
## Chain 1 Iteration:   600 / 2000 [ 30%] (Warmup)
## Chain 1 Iteration:   700 / 2000 [ 35%] (Warmup)
## Chain 1 Iteration:   800 / 2000 [ 40%] (Warmup)
## Chain 1 Iteration:   900 / 2000 [ 45%] (Warmup)
## Chain 1 Iteration:  1000 / 2000 [ 50%] (Warmup)
## Chain 1 Iteration:  1001 / 2000 [ 50%] (Sampling)
## Chain 1 Iteration:  1100 / 2000 [ 55%] (Sampling)
## Chain 2 Iteration:    1 / 2000 [  0%] (Warmup)
## Chain 2 Iteration:   100 / 2000 [  5%] (Warmup)
## Chain 2 Iteration:   200 / 2000 [ 10%] (Warmup)
## Chain 2 Iteration:   300 / 2000 [ 15%] (Warmup)
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## Chain 2 Iteration:   600 / 2000 [ 30%] (Warmup)
## Chain 2 Iteration:   700 / 2000 [ 35%] (Warmup)
## Chain 2 Iteration:   800 / 2000 [ 40%] (Warmup)
## Chain 2 Iteration:   900 / 2000 [ 45%] (Warmup)
## Chain 2 Iteration:  1000 / 2000 [ 50%] (Warmup)
## Chain 2 Iteration:  1001 / 2000 [ 50%] (Sampling)
```

```

## Chain 2 Iteration: 1100 / 2000 [ 55%] (Sampling)
## Chain 3 Iteration:   1 / 2000 [  0%] (Warmup)
## Chain 3 Iteration: 100 / 2000 [  5%] (Warmup)
## Chain 3 Iteration: 200 / 2000 [ 10%] (Warmup)
## Chain 3 Iteration: 300 / 2000 [ 15%] (Warmup)
## Chain 3 Iteration: 400 / 2000 [ 20%] (Warmup)
## Chain 3 Iteration: 500 / 2000 [ 25%] (Warmup)
## Chain 3 Iteration: 600 / 2000 [ 30%] (Warmup)
## Chain 3 Iteration: 700 / 2000 [ 35%] (Warmup)
## Chain 3 Iteration: 800 / 2000 [ 40%] (Warmup)
## Chain 3 Iteration: 900 / 2000 [ 45%] (Warmup)
## Chain 3 Iteration: 1000 / 2000 [ 50%] (Warmup)
## Chain 3 Iteration: 1001 / 2000 [ 50%] (Sampling)
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## Chain 3 Iteration: 1400 / 2000 [ 70%] (Sampling)
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## Chain 3 Iteration: 1700 / 2000 [ 85%] (Sampling)
## Chain 3 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 3 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 3 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 1 finished in 0.2 seconds.
## Chain 2 finished in 0.2 seconds.
## Chain 3 finished in 0.2 seconds.
##
## All 3 chains finished successfully.
## Mean chain execution time: 0.2 seconds.
## Total execution time: 0.2 seconds.

```

```

xres <- precis(models$koram, depth = 2)
xres_link <- apply(xres[,c(1:4)], 2, inv_logit)
xres_link <- cbind(xres_link, xres[c("n_eff", "Rhat4")])
xres_link$n_eff <- round(xres_link$n_eff)
xres_link$Rhat4 <- round(xres_link$Rhat4, 2)

```

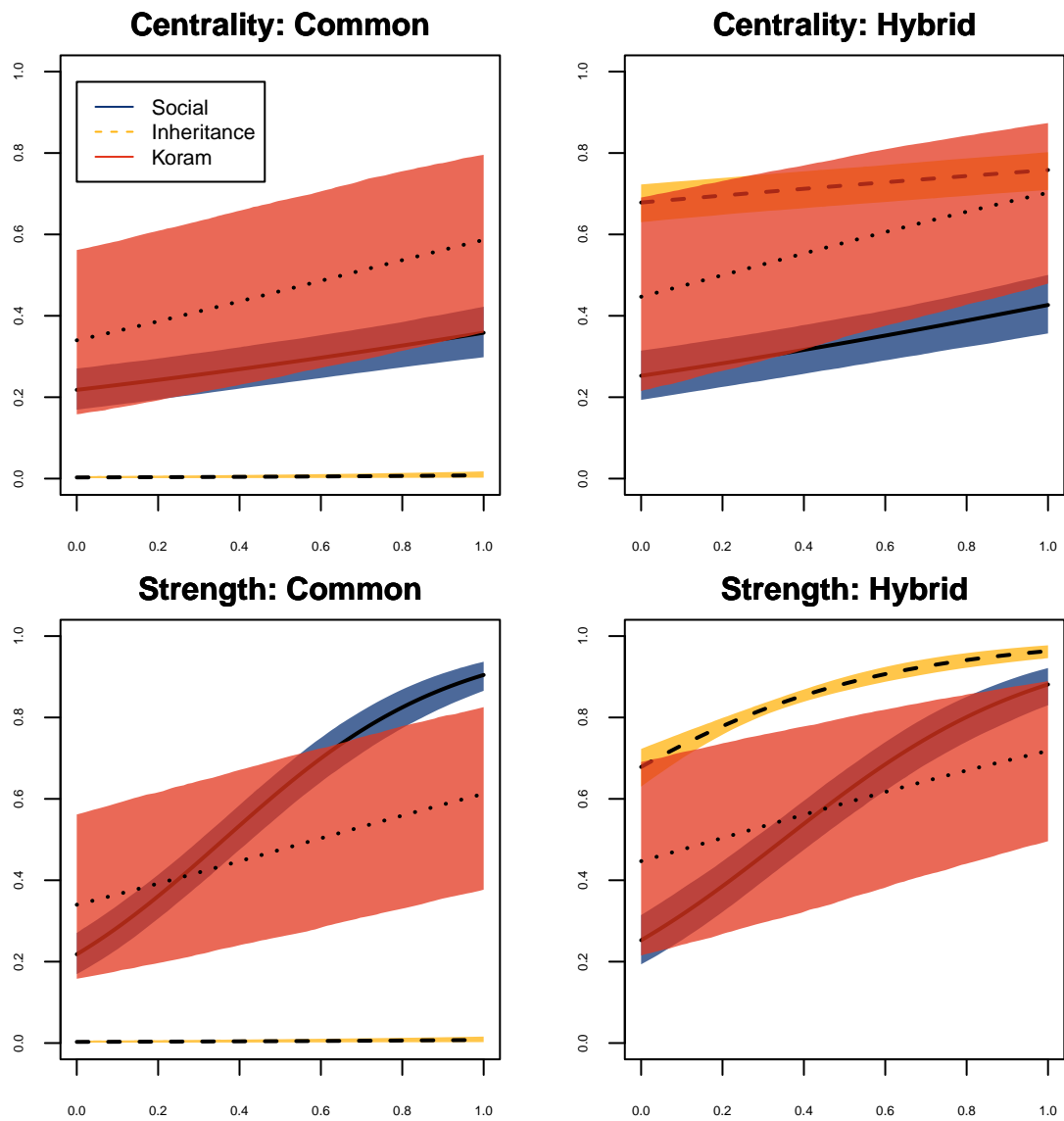


```
write.csv(xres_link, "../Tables/csvs/koram_precis_link.csv")
```

Plotting the Result

```
names(models) <- c("Social",  
                  "Inheritance",  
                  "Koram")
```

```
figure_1(models)
```



```
## NULL
```

Analysis of Alternative: Resource Attraction

A new list to put the alternative hypotheses data in.

```
amodels <- list()
```

ABM N Attractors = 1, Attractor Strength = 25

```
nodes <- read.csv("../Data/ABM_Asocial_naias25_Condition.csv")

set.seed(11)

dat <- list(
  U = nodes$U,
  C = nodes$C,
  S = nodes$S,
  A = nodes$A,
  H = nodes$H
)

amodels$naias25 <- ulam(
  model_spec,
  data = dat,
  chains = N_CHAINS,
  cores = 10,
  iter = 2000,
  log_lik = TRUE,
  cmdstan = TRUE
)
```

```
## Running MCMC with 3 chains, at most 10 in parallel, with 1 thread(s) per chain...
##
```

```
## Chain 1 Iteration:    1 / 2000 [  0%]  (Warmup)
```

```
## Chain 1 Informational Message: The current Metropolis proposal is about to be rejected because of the
```

```
## Chain 1 Exception: binomial_lpmf: Probability parameter[4] is nan, but must be in the interval [0, 1]
```

```
## Chain 1 If this warning occurs sporadically, such as for highly constrained variable types like covariance
```

```
## Chain 1 but if this warning occurs often then your model may be either severely ill-conditioned or misspecified
```

```
## Chain 1
```

```
## Chain 2 Iteration:    1 / 2000 [  0%]  (Warmup)
```

```
## Chain 2 Informational Message: The current Metropolis proposal is about to be rejected because of the
```

```
## Chain 2 Exception: binomial_lpmf: Probability parameter[4] is nan, but must be in the interval [0, 1]
```

Chain 2 If this warning occurs sporadically, such as for highly constrained variable types like covar

Chain 2 but if this warning occurs often then your model may be either severely ill-conditioned or m

Chain 2

```
## Chain 3 Iteration:    1 / 2000 [ 0%] (Warmup)
## Chain 1 Iteration:   100 / 2000 [ 5%] (Warmup)
## Chain 2 Iteration:   100 / 2000 [ 5%] (Warmup)
## Chain 3 Iteration:   100 / 2000 [ 5%] (Warmup)
## Chain 2 Iteration:   200 / 2000 [ 10%] (Warmup)
## Chain 3 Iteration:   200 / 2000 [ 10%] (Warmup)
## Chain 1 Iteration:   200 / 2000 [ 10%] (Warmup)
## Chain 2 Iteration:   300 / 2000 [ 15%] (Warmup)
## Chain 3 Iteration:   300 / 2000 [ 15%] (Warmup)
## Chain 1 Iteration:   300 / 2000 [ 15%] (Warmup)
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## Chain 1 Iteration:   400 / 2000 [ 20%] (Warmup)
## Chain 2 Iteration:   500 / 2000 [ 25%] (Warmup)
## Chain 3 Iteration:   500 / 2000 [ 25%] (Warmup)
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## Chain 1 Iteration:   500 / 2000 [ 25%] (Warmup)
## Chain 3 Iteration:   600 / 2000 [ 30%] (Warmup)
## Chain 1 Iteration:   600 / 2000 [ 30%] (Warmup)
## Chain 2 Iteration:   700 / 2000 [ 35%] (Warmup)
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## Chain 2 Iteration:   800 / 2000 [ 40%] (Warmup)
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## Chain 2 Iteration:   900 / 2000 [ 45%] (Warmup)
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## Chain 2 Iteration:  1000 / 2000 [ 50%] (Warmup)
## Chain 2 Iteration:  1001 / 2000 [ 50%] (Sampling)
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## Chain 3 Iteration:  1100 / 2000 [ 55%] (Sampling)
## Chain 1 Iteration:  1100 / 2000 [ 55%] (Sampling)
## Chain 3 Iteration:  1200 / 2000 [ 60%] (Sampling)
## Chain 2 Iteration:  1200 / 2000 [ 60%] (Sampling)
## Chain 1 Iteration:  1200 / 2000 [ 60%] (Sampling)
## Chain 3 Iteration:  1300 / 2000 [ 65%] (Sampling)
## Chain 2 Iteration:  1300 / 2000 [ 65%] (Sampling)
## Chain 1 Iteration:  1300 / 2000 [ 65%] (Sampling)
## Chain 3 Iteration:  1400 / 2000 [ 70%] (Sampling)
## Chain 1 Iteration:  1400 / 2000 [ 70%] (Sampling)
## Chain 2 Iteration:  1400 / 2000 [ 70%] (Sampling)
## Chain 3 Iteration:  1500 / 2000 [ 75%] (Sampling)
```

```

## Chain 1 Iteration: 1500 / 2000 [ 75%] (Sampling)
## Chain 2 Iteration: 1500 / 2000 [ 75%] (Sampling)
## Chain 3 Iteration: 1600 / 2000 [ 80%] (Sampling)
## Chain 1 Iteration: 1600 / 2000 [ 80%] (Sampling)
## Chain 3 Iteration: 1700 / 2000 [ 85%] (Sampling)
## Chain 2 Iteration: 1600 / 2000 [ 80%] (Sampling)
## Chain 1 Iteration: 1700 / 2000 [ 85%] (Sampling)
## Chain 3 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 1 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 2 Iteration: 1700 / 2000 [ 85%] (Sampling)
## Chain 3 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 1 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 2 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 3 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 3 finished in 11.7 seconds.
## Chain 1 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 1 finished in 11.9 seconds.
## Chain 2 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 2 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 2 finished in 12.8 seconds.
##
## All 3 chains finished successfully.
## Mean chain execution time: 12.1 seconds.
## Total execution time: 12.8 seconds.

```

```

xres <- precis(amodels$na1as25, depth = 2)
xres_link <- apply(xres[,c(1:4)], 2, inv_logit)
xres_link <- cbind(xres_link, xres[c("n_eff", "Rhat4")])
xres_link$n_eff <- round(xres_link$n_eff)
xres_link$Rhat4 <- round(xres_link$Rhat4, 2)
write.csv(xres_link, "../Tables/csvs/na1as25_precis_link.csv")

```

ABM N Attractors = 10, Attractor Strength = 25

```

nodes <- read.csv("../Data/ABM_Asocial_na10as25_Condition.csv")

set.seed(11)

dat <- list(
  U = nodes$U,
  C = nodes$C,
  S = nodes$S,
  A = nodes$A,
  H = nodes$H
)

amodels$na10as25 <- ulam(
  model_spec,
  data = dat,
  chains = N_CHAINS,
  cores = 10,
  iter = 2000,

```

```

log_lik = TRUE,
cmdstan = TRUE # only needed on macbook air M1
)

```

```
## Running MCMC with 3 chains, at most 10 in parallel, with 1 thread(s) per chain...
```

```
##
```

```
## Chain 1 Iteration:    1 / 2000 [  0%] (Warmup)
```

```
## Chain 1 Informational Message: The current Metropolis proposal is about to be rejected because of the
```

```
## Chain 1 Exception: binomial_lpmf: Probability parameter[31] is nan, but must be in the interval [0, 1]
```

```
## Chain 1 If this warning occurs sporadically, such as for highly constrained variable types like covariance
```

```
## Chain 1 but if this warning occurs often then your model may be either severely ill-conditioned or misspecified
```

```
## Chain 1
```

```
## Chain 2 Iteration:    1 / 2000 [  0%] (Warmup)
```

```
## Chain 2 Informational Message: The current Metropolis proposal is about to be rejected because of the
```

```
## Chain 2 Exception: binomial_lpmf: Probability parameter[265] is nan, but must be in the interval [0, 1]
```

```
## Chain 2 If this warning occurs sporadically, such as for highly constrained variable types like covariance
```

```
## Chain 2 but if this warning occurs often then your model may be either severely ill-conditioned or misspecified
```

```
## Chain 2
```

```
## Chain 3 Iteration:    1 / 2000 [  0%] (Warmup)
```

```
## Chain 1 Iteration:   100 / 2000 [  5%] (Warmup)
```

```
## Chain 2 Iteration:   100 / 2000 [  5%] (Warmup)
```

```
## Chain 3 Iteration:   100 / 2000 [  5%] (Warmup)
```

```
## Chain 2 Iteration:   200 / 2000 [ 10%] (Warmup)
```

```
## Chain 1 Iteration:   200 / 2000 [ 10%] (Warmup)
```

```
## Chain 3 Iteration:   200 / 2000 [ 10%] (Warmup)
```

```
## Chain 2 Iteration:   300 / 2000 [ 15%] (Warmup)
```

```
## Chain 1 Iteration:   300 / 2000 [ 15%] (Warmup)
```

```
## Chain 3 Iteration:   300 / 2000 [ 15%] (Warmup)
```

```
## Chain 2 Iteration:   400 / 2000 [ 20%] (Warmup)
```

```
## Chain 1 Iteration:   400 / 2000 [ 20%] (Warmup)
```

```
## Chain 3 Iteration:   400 / 2000 [ 20%] (Warmup)
```

```
## Chain 1 Iteration:   500 / 2000 [ 25%] (Warmup)
```

```
## Chain 2 Iteration:   500 / 2000 [ 25%] (Warmup)
```

```
## Chain 3 Iteration:   500 / 2000 [ 25%] (Warmup)
```

```
## Chain 1 Iteration:   600 / 2000 [ 30%] (Warmup)
```

```
## Chain 2 Iteration:   600 / 2000 [ 30%] (Warmup)
```

```
## Chain 3 Iteration:   600 / 2000 [ 30%] (Warmup)
```

```
## Chain 1 Iteration:   700 / 2000 [ 35%] (Warmup)
```

```

## Chain 2 Iteration: 700 / 2000 [ 35%] (Warmup)
## Chain 3 Iteration: 700 / 2000 [ 35%] (Warmup)
## Chain 1 Iteration: 800 / 2000 [ 40%] (Warmup)
## Chain 2 Iteration: 800 / 2000 [ 40%] (Warmup)
## Chain 3 Iteration: 800 / 2000 [ 40%] (Warmup)
## Chain 1 Iteration: 900 / 2000 [ 45%] (Warmup)
## Chain 2 Iteration: 900 / 2000 [ 45%] (Warmup)
## Chain 3 Iteration: 900 / 2000 [ 45%] (Warmup)
## Chain 2 Iteration: 1000 / 2000 [ 50%] (Warmup)
## Chain 2 Iteration: 1001 / 2000 [ 50%] (Sampling)
## Chain 1 Iteration: 1000 / 2000 [ 50%] (Warmup)
## Chain 1 Iteration: 1001 / 2000 [ 50%] (Sampling)
## Chain 3 Iteration: 1000 / 2000 [ 50%] (Warmup)
## Chain 3 Iteration: 1001 / 2000 [ 50%] (Sampling)
## Chain 2 Iteration: 1100 / 2000 [ 55%] (Sampling)
## Chain 1 Iteration: 1100 / 2000 [ 55%] (Sampling)
## Chain 3 Iteration: 1100 / 2000 [ 55%] (Sampling)
## Chain 2 Iteration: 1200 / 2000 [ 60%] (Sampling)
## Chain 1 Iteration: 1200 / 2000 [ 60%] (Sampling)
## Chain 3 Iteration: 1200 / 2000 [ 60%] (Sampling)
## Chain 2 Iteration: 1300 / 2000 [ 65%] (Sampling)
## Chain 1 Iteration: 1300 / 2000 [ 65%] (Sampling)
## Chain 3 Iteration: 1300 / 2000 [ 65%] (Sampling)
## Chain 2 Iteration: 1400 / 2000 [ 70%] (Sampling)
## Chain 3 Iteration: 1400 / 2000 [ 70%] (Sampling)
## Chain 1 Iteration: 1400 / 2000 [ 70%] (Sampling)
## Chain 2 Iteration: 1500 / 2000 [ 75%] (Sampling)
## Chain 3 Iteration: 1500 / 2000 [ 75%] (Sampling)
## Chain 1 Iteration: 1500 / 2000 [ 75%] (Sampling)
## Chain 2 Iteration: 1600 / 2000 [ 80%] (Sampling)
## Chain 3 Iteration: 1600 / 2000 [ 80%] (Sampling)
## Chain 1 Iteration: 1600 / 2000 [ 80%] (Sampling)
## Chain 3 Iteration: 1700 / 2000 [ 85%] (Sampling)
## Chain 2 Iteration: 1700 / 2000 [ 85%] (Sampling)
## Chain 1 Iteration: 1700 / 2000 [ 85%] (Sampling)
## Chain 2 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 3 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 1 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 2 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 3 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 1 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 2 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 3 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 2 finished in 11.6 seconds.
## Chain 3 finished in 11.6 seconds.
## Chain 1 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 1 finished in 11.8 seconds.
##
## All 3 chains finished successfully.
## Mean chain execution time: 11.7 seconds.
## Total execution time: 11.9 seconds.

```

```

xres <- precis(amodels$na10as25, depth = 2)
xres_link <- apply(xres[,c(1:4)], 2, inv_logit)

```

```
xres_link <- cbind(xres_link, xres[c("n_eff", "Rhat4")])
xres_link$n_eff <- round(xres_link$n_eff)
xres_link$Rhat4 <- round(xres_link$Rhat4, 2)
write.csv(xres_link, "../Tables/csvs/na10as25_precis_link.csv")
```

ABM N Attractors = 200, Attractor Strength = 25

```
nodes <- read.csv("../Data/ABM_Asocial_na200as25_Condition.csv")

set.seed(11)

dat <- list(
  U = nodes$U,
  C = nodes$C,
  S = nodes$S,
  A = nodes$A,
  H = nodes$H
)

amodels$na200as25 <- ulam(
  model_spec,
  data = dat,
  chains = N_CHAINS,
  cores = 10,
  iter = 2000,
  log_lik = TRUE,
  cmdstan = TRUE # only needed on macbook air M1
)
```

```
## Running MCMC with 3 chains, at most 10 in parallel, with 1 thread(s) per chain...
```

```
##
```

```
## Chain 1 Iteration:    1 / 2000 [ 0%] (Warmup)
```

```
## Chain 1 Informational Message: The current Metropolis proposal is about to be rejected because of the
```

```
## Chain 1 Exception: binomial_lpmf: Probability parameter[36] is nan, but must be in the interval [0,
```

```
## Chain 1 If this warning occurs sporadically, such as for highly constrained variable types like covariates,
```

```
## Chain 1 but if this warning occurs often then your model may be either severely ill-conditioned or misspecified.
```

```
## Chain 1
```

```
## Chain 2 Iteration:    1 / 2000 [ 0%] (Warmup)
```

```
## Chain 2 Informational Message: The current Metropolis proposal is about to be rejected because of the
```

```
## Chain 2 Exception: binomial_lpmf: Probability parameter[171] is nan, but must be in the interval [0,
```

Chain 2 If this warning occurs sporadically, such as for highly constrained variable types like covar

Chain 2 but if this warning occurs often then your model may be either severely ill-conditioned or m

Chain 2

```
## Chain 3 Iteration:    1 / 2000 [ 0%] (Warmup)
## Chain 3 Iteration:   100 / 2000 [ 5%] (Warmup)
## Chain 1 Iteration:   100 / 2000 [ 5%] (Warmup)
## Chain 2 Iteration:   100 / 2000 [ 5%] (Warmup)
## Chain 2 Iteration:   200 / 2000 [ 10%] (Warmup)
## Chain 3 Iteration:   200 / 2000 [ 10%] (Warmup)
## Chain 1 Iteration:   200 / 2000 [ 10%] (Warmup)
## Chain 2 Iteration:   300 / 2000 [ 15%] (Warmup)
## Chain 1 Iteration:   300 / 2000 [ 15%] (Warmup)
## Chain 3 Iteration:   300 / 2000 [ 15%] (Warmup)
## Chain 1 Iteration:   400 / 2000 [ 20%] (Warmup)
## Chain 2 Iteration:   400 / 2000 [ 20%] (Warmup)
## Chain 3 Iteration:   400 / 2000 [ 20%] (Warmup)
## Chain 2 Iteration:   500 / 2000 [ 25%] (Warmup)
## Chain 3 Iteration:   500 / 2000 [ 25%] (Warmup)
## Chain 1 Iteration:   500 / 2000 [ 25%] (Warmup)
## Chain 2 Iteration:   600 / 2000 [ 30%] (Warmup)
## Chain 3 Iteration:   600 / 2000 [ 30%] (Warmup)
## Chain 1 Iteration:   600 / 2000 [ 30%] (Warmup)
## Chain 2 Iteration:   700 / 2000 [ 35%] (Warmup)
## Chain 3 Iteration:   700 / 2000 [ 35%] (Warmup)
## Chain 1 Iteration:   700 / 2000 [ 35%] (Warmup)
## Chain 2 Iteration:   800 / 2000 [ 40%] (Warmup)
## Chain 3 Iteration:   800 / 2000 [ 40%] (Warmup)
## Chain 1 Iteration:   800 / 2000 [ 40%] (Warmup)
## Chain 2 Iteration:   900 / 2000 [ 45%] (Warmup)
## Chain 3 Iteration:   900 / 2000 [ 45%] (Warmup)
## Chain 1 Iteration:   900 / 2000 [ 45%] (Warmup)
## Chain 2 Iteration:  1000 / 2000 [ 50%] (Warmup)
## Chain 2 Iteration:  1001 / 2000 [ 50%] (Sampling)
## Chain 3 Iteration:  1000 / 2000 [ 50%] (Warmup)
## Chain 3 Iteration:  1001 / 2000 [ 50%] (Sampling)
## Chain 1 Iteration:  1000 / 2000 [ 50%] (Warmup)
## Chain 1 Iteration:  1001 / 2000 [ 50%] (Sampling)
## Chain 2 Iteration:  1100 / 2000 [ 55%] (Sampling)
## Chain 3 Iteration:  1100 / 2000 [ 55%] (Sampling)
## Chain 1 Iteration:  1100 / 2000 [ 55%] (Sampling)
## Chain 2 Iteration:  1200 / 2000 [ 60%] (Sampling)
## Chain 3 Iteration:  1200 / 2000 [ 60%] (Sampling)
## Chain 1 Iteration:  1200 / 2000 [ 60%] (Sampling)
## Chain 2 Iteration:  1300 / 2000 [ 65%] (Sampling)
## Chain 3 Iteration:  1300 / 2000 [ 65%] (Sampling)
## Chain 1 Iteration:  1300 / 2000 [ 65%] (Sampling)
## Chain 3 Iteration:  1400 / 2000 [ 70%] (Sampling)
## Chain 2 Iteration:  1400 / 2000 [ 70%] (Sampling)
## Chain 1 Iteration:  1400 / 2000 [ 70%] (Sampling)
## Chain 2 Iteration:  1500 / 2000 [ 75%] (Sampling)
```



```

## Chain 3 Iteration: 1500 / 2000 [ 75%] (Sampling)
## Chain 1 Iteration: 1500 / 2000 [ 75%] (Sampling)
## Chain 3 Iteration: 1600 / 2000 [ 80%] (Sampling)
## Chain 2 Iteration: 1600 / 2000 [ 80%] (Sampling)
## Chain 1 Iteration: 1600 / 2000 [ 80%] (Sampling)
## Chain 3 Iteration: 1700 / 2000 [ 85%] (Sampling)
## Chain 2 Iteration: 1700 / 2000 [ 85%] (Sampling)
## Chain 1 Iteration: 1700 / 2000 [ 85%] (Sampling)
## Chain 3 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 2 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 1 Iteration: 1800 / 2000 [ 90%] (Sampling)
## Chain 3 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 2 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 1 Iteration: 1900 / 2000 [ 95%] (Sampling)
## Chain 3 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 3 finished in 9.3 seconds.
## Chain 2 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 2 finished in 9.4 seconds.
## Chain 1 Iteration: 2000 / 2000 [100%] (Sampling)
## Chain 1 finished in 9.6 seconds.
##
## All 3 chains finished successfully.
## Mean chain execution time: 9.4 seconds.
## Total execution time: 9.7 seconds.

```

```

xres <- precis(amodels$na200as25, depth = 2)
xres_link <- apply(xres[,c(1:4)], 2, inv_logit)
xres_link <- cbind(xres_link, xres[c("n_eff", "Rhat4")])
xres_link$n_eff <- round(xres_link$n_eff)
xres_link$Rhat4 <- round(xres_link$Rhat4, 2)
write.csv(xres_link, "../Tables/csvs/na200as25_precis_link.csv")

```

```

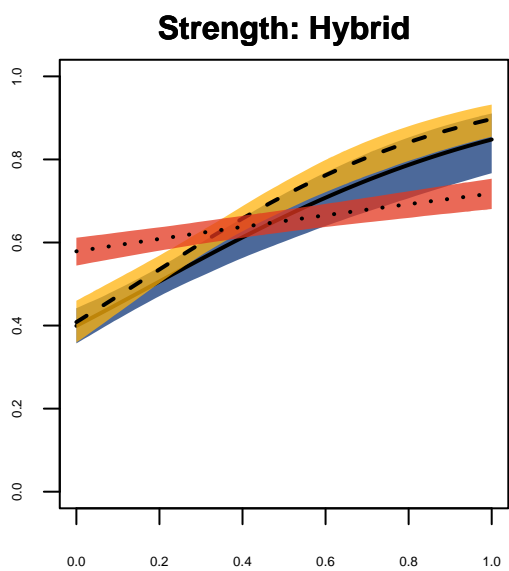
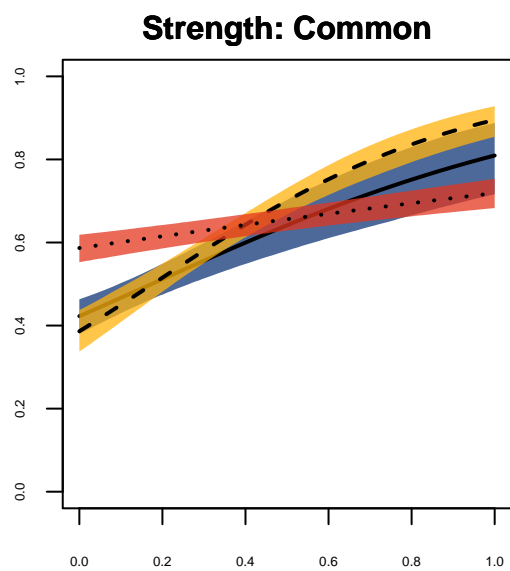
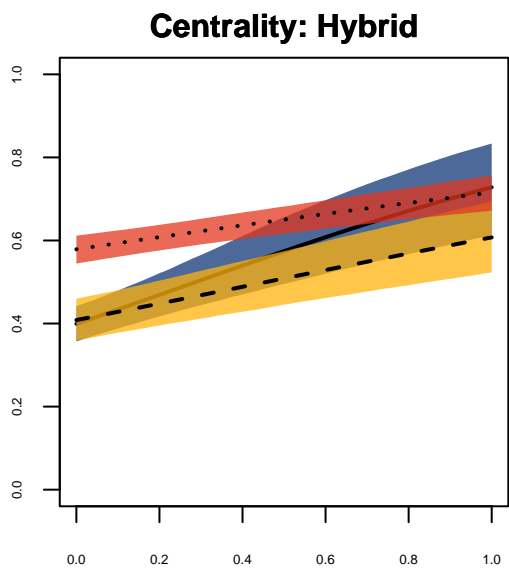
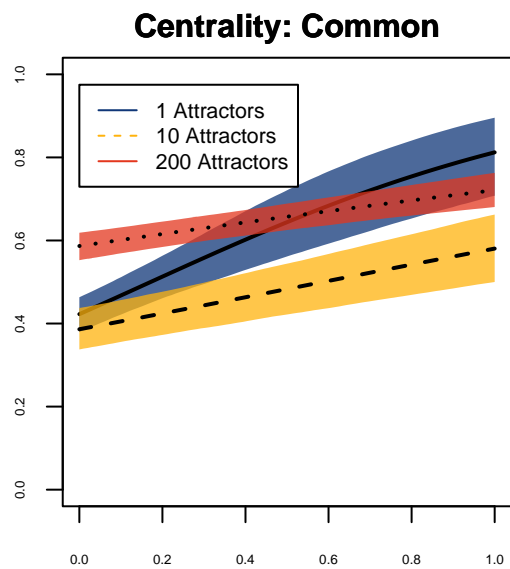
names(amodels) <- c("1 Attractors",
                    "10 Attractors",
                    "200 Attractors")

```

```

figure_1(amodels)

```



NULL