Kasdin et al. (2025) show that dopamine in the brains of young zebra finches acts as a learning signal, increasing when they sing closer to their adult song and decreasing when they sing further away, effectively guiding their vocal development through trial-and-error. This suggests that complex natural behaviors, like learning to sing, are shaped by dopamine-driven reinforcement learning, similar to how artificial intelligence learns. You can find the paper at this link: https://www.nature.com/articles/s41586-025-08729-1..

Note they measure dopamine using fibre photometry, changes in the fluorescence indicate dopamine changes in realtime. Their specific measurement considers changes in flourescence in 100-ms windows between 200 and 300 ms from the start of singing, averaged across development.

1. Using the `pwr` package for `R` (Champely, 2020), conduct a power analysis. How many observations would the researchers need to detect a moderate-to-large effect ($d = 0.65$) when using $\alpha = 0.05$ and default power (0.80) for a two-sided one sample t test.

```
alpha <- 0.05
(pwr.analysis <- pwr.t.test(d=0.65, sig.level = alpha, power = 0.80,
                            type = "one.sample", alternative = "two.sided"))

##
##      One-sample t test power calculation
##
##               n = 20.58039
##               d = 0.65
##       sig.level = 0.05
##           power = 0.8
##     alternative = two.sided
```

Solution: Using the `pwr.t.test()` function from the `pwr` package, the number of observations the researchers would need is $n = 20.58$. In this study, the researchers used $n = 25$ observation, well over the number of observations necessary.

2. Click the link to go to the paper. Find the source data for Figure 2. Download the Excel file. Describe what you needed to do to collect the data for Figure 2(g). Note that you only need the `closer_vals` and `further_vals`. Ensure to `mutate()` the data to get a difference (e.g., `closer_vals - further_vals`).

```
# closer vals
closer.data <- read_csv("closer_vals.csv")
# further vals
further.data <- read_csv("further_vals.csv")

# consolidate all data
figG.data <- tibble(closer_vals = closer.data$closer_vals,
                    further_vals = further.data$further_vals) |>
  mutate(val_diffs = closer_vals - further_vals)
# create table for sweave
xtable(figG.data)
```

Solution: The code snippet above shows the code used for creating the table and generating the table (Table 1) shown on the next page, using `xtable` (Dahl et al., 2019).

observation	closer_vals	further_vals	val_diffs
1	0.28	-0.19	0.47
2	0.08	-0.03	0.11
3	0.13	-0.19	0.32
4	0.04	-0.07	0.11
5	0.15	-0.09	0.23
6	0.20	-0.16	0.36
7	0.16	-0.31	0.47
8	0.18	-0.16	0.34
9	0.13	-0.13	0.26
10	0.10	-0.05	0.15
11	0.33	-0.60	0.93
12	0.17	-0.24	0.41
13	0.07	-0.12	0.20
14	0.00	-0.13	0.13
15	0.00	-0.04	0.04
16	0.09	-0.24	0.33
17	0.26	-0.34	0.61
18	0.28	-0.31	0.59
19	0.07	-0.18	0.25
20	0.15	-0.07	0.23
21	0.27	-0.34	0.61
22	0.15	-0.19	0.34
23	0.10	-0.20	0.30
24	0.19	-0.31	0.50
25	0.34	-0.35	0.69

Table 1: Table showing values for `closer_vals`, `further_vals`, and their corresponding differences (`val_diffs`).

3. Summarize the data.

   (a) Summarize the further data. Do the data suggest that dopamine in the brains of young zebra finches decreases when they sing further away?

```
# part A
further.summary <- summarize(figG.data,
                             mean = mean(further_vals),
                             variance = var(further_vals),
                             median = median(further_vals),
                             IQR = IQR(further_vals),
                             skewness = skewness(further_vals),
                             e.kurtosis = kurtosis(further_vals))
xtable(further.summary)
```

Solution: Above is a code snippet used to generate a table of summary statistics (Table 2) for the further data. Since the mean and median are both negative, this suggests that dopamine is decreasing for further values. Some functions used to calculate summary statistics came from the `e1071` (Meyer et al., 2024) package.

mean	variance	median	IQR	skewness	e.kurtosis
-0.20	0.02	-0.19	0.19	-1.04	1.19

Table 2: Summary Statistics for further data.

(b) Summarize the closer data. Do the data suggest that dopamine in the brains of young zebra finches increases when they sing closer to their adult song?

```
# part B
closer.summary <- summarize(figG.data,
                            mean = mean(closer_vals),
                            variance = var(closer_vals),
                            median = median(closer_vals),
                            IQR = IQR(closer_vals),
                            skewness = skewness(closer_vals),
                            e.kurtosis = kurtosis(closer_vals))
xtable(closer.summary)
```

Solution: Above is a code snippet used to generate a table of summary statistics (Table 3) for the closer data. Since the mean and median are both positive, this suggests that dopamine is increasing for closer values.

mean	variance	median	IQR	skewness	e.kurtosis
0.16	0.01	0.15	0.11	0.30	-0.86

Table 3: Summary Statistics for closer data.

(c) Summarize the paired differences. Do the data suggest that there is a difference between dopamine in the brains of young zebra finches when they sing further away compared to closer to their adult song?

Solution: Above is a code snippet used to generate a table of summary statistics (Table 4) for the paired differences. Since the mean and median are both positive, this suggests that dopamine is changing in paired differences.

mean	variance	median	IQR	skewness	e.kurtosis
0.36	-0.01	0.33	-0.08	1.33	-2.05

Table 4: Summary Statistics for paired differences.

(d) **Optional Challenge:** Can you reproduce Figure 2(g)? Note that the you can use `geom_errorbar()` to plot the range created by adding the mean $\pm$ one standard deviation.

4. Conduct the inferences they do in the paper. Make sure to report the results a little more comprehensively – that is your parenthetical should look something like: ($t = 23.99$, $p < 0.0001$; $g = 1.34$; 95% CI: 4.43, 4.60).
Note: Your numbers may vary slightly as they performed some unclear correction of their p-values. I'm waiting to hear back from them via email!

(a) "The close responses differed significantly from 0 ($p = 1.63 \times 10^{-8}$)."

```
# part A (closer)
mu0 <- 0
x <- figG.data$closer_vals

# hedge's g + CI
hedges_g(x = x, mu = mu0, alternative = "greater")

## Hedges' g |      95% CI
## ------------------------
## 1.61      | [1.10, Inf]
```

```
##
## - One-sided CIs: upper bound fixed at [Inf].
```

```
interpret_hedges_g(1.61)
```

```
## [1] "large"
## (Rules: cohen1988)
```

```
# t.test
t.test(x=x, mu = mu0, alternative = "greater")
```

```
##
##  One Sample t-test
##
## data:  x
## t = 8.3024, df = 24, p-value = 8.132e-09
## alternative hypothesis: true mean is greater than 0
## 95 percent confidence interval:
##  0.1240301       Inf
## sample estimates:
## mean of x
## 0.1562231
```

Solution: Since we expect dopamine levels to increase when the responses are closer, we want to use a right-tailed test. This givens us the results:

$$(t = 8.30;\ p = 8.13 * 10^{-9};\ g = 1.61;\ 95\%\ \text{CI: } 0.124, \text{Inf})$$

The functions used to accomplish these tasks (`hedges_g(), t.test()`), came from the `effectsize` (Ben-Shachar et al., 2020) package.

(b) "The far responses differed significantly from 0 ($p = 5.17 \times 10^{-8}$)."

```
# part B (further)
mu0 <- 0
x <- figG.data$further_vals

# hedge's g + CI
hedges_g(x = x, mu = mu0, alternative = "less")
```

```
## Hedges' g |         95% CI
## -------------------------
## -1.51     | [-Inf, -1.02]
##
## - One-sided CIs: lower bound fixed at [-Inf].
```

```
interpret_hedges_g(-1.51)
```

```
## [1] "large"
## (Rules: cohen1988)
```

```
# t.test
t.test(x=x, mu = mu0, alternative = "less")
```

```
##
##  One Sample t-test
##
## data:  x
## t = -7.778, df = 24, p-value = 2.587e-08
```

```
## alternative hypothesis: true mean is less than 0
## 95 percent confidence interval:
##        -Inf -0.1581322
## sample estimates:
##  mean of x
## -0.2027244
```

Solution: Since we expect dopamine levels to decrease when the responses are further, we want to use a left-tailed test. This givens us the results:

$$(t = -7.78;\ p = 2.59 * 10^{-8};\ g = -1.51;\ 95\%\ \text{CI: -Inf, -0.158})$$

(c) "The difference between populations was significant ($p = 1.04 \times 10^{-8}$)."

```
# part C (differences)
mu0 <- 0
x <- figG.data$val_diffs

# hedge's g + CI
hedges_g(x = x, mu = mu0, alternative = "two.sided")

## Hedges' g |       95% CI
## ------------------------
## 1.65      | [1.04, 2.24]

interpret_hedges_g(1.65)

## [1] "large"
## (Rules: cohen1988)

# t.test
t.test(x=x, mu = mu0, alternative = "two.sided")

##
##  One Sample t-test
##
## data:  x
## t = 8.5109, df = 24, p-value = 1.037e-08
## alternative hypothesis: true mean is not equal to 0
## 95 percent confidence interval:
##  0.2719028 0.4459921
## sample estimates:
## mean of x
## 0.3589475
```

Solution: Since we expect the difference to be significant between populations, we want to use a two-tailed test. This givens us the results:

$$(t = 8.51;\ p = 1.04 * 10^{-8};\ g = 1.65;\ 95\%\ \text{CI: 0.272, 0.446})$$

5. Reverse engineer the hypothesis test plot from Lecture 20 to create accurate hypothesis testing plots for each part of the previous question.

   (a) Question 4, part(a).

   (b) Question 4, part(b).

   (c) Question 4, part(c).

References

Ben-Shachar, M. S., Lüdecke, D., and Makowski, D. (2020). effectsize: Estimation of effect size indices and standardized parameters. *Journal of Open Source Software*, 5(56):2815.

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Dahl, D. B., Scott, D., Roosen, C., Magnusson, A., and Swinton, J. (2019). *xtable: Export Tables to LaTeX or HTML*. R package version 1.8-4.

Kasdin, J., Duffy, A., Nadler, N., Raha, A., Fairhall, A. L., Stachenfeld, K. L., and Gadagkar, V. (2025). Natural behaviour is learned through dopamine-mediated reinforcement. *Nature*, pages 1–8.

Meyer, D., Dimitriadou, E., Hornik, K., Weingessel, A., and Leisch, F. (2024). *e1071: Misc Functions of the Department of Statistics, Probability Theory Group (Formerly: E1071), TU Wien*. R package version 1.7-16.