# CSE 599K

## Empirical Research Methods

Winter 2025

**SE meets Science**

# Today

- Recap: analysis validity
- SE principles for rigorous Science
- Two example studies

# Analysis validity

# Analysis validity: open questions

**External validity**

- Does the experiment generalize (to larger population, other subjects, etc.)?
- How representative is the sample?

**Internal validity**

- Does the experiment isolate the variable(s) of interest?
- Does the experiment control for confounders and unwanted effects?

**Construct validity**

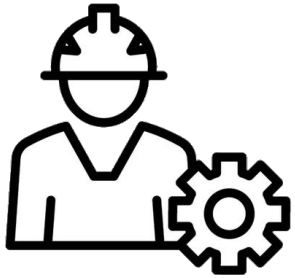
- Does the experiment measure what it claims to measure?
- Do the proxy measures and tools adequately measure the concept of interest?

**(Statistical) conclusion validity**

- Are the conclusions valid based on the chosen statistical test and sample size?
- Are the conclusions valid based on the observed significance (p value)?

# SE principles for rigorous science

# Science to practice is not a one-way street!

Let’s improve **scientific rigor** with
**SE principles** and **best practices!**

# Design reviews

Design reviews are common in practice.

Embrace and value **pre-registrations**.

RFCs and public discussions (e.g., GH) provide valuable context.

**Public (open) reviews** should be a no-brainer!

*Hark no more: On the preregistration of chi experiments,* Cockburn et al., CHI 2018
*https://openreview.net/*

# Quality assurance

Modern code review is incremental (not holistic).

Move to **pre-acceptance artifact evaluations.**

Software testing is the most common QA approach in practice.

Require **evidence for artifact testing**.

*Expectations, outcomes, and challenges of modern code review*, Bacchelli and Bird, ICSE 2013
*Modern code review: a case study at Google,* Sadowski et al., ICSE 2018

# Process

Merge conflicts (branches) are resolved by branch authors.

Expect **resolution** (knowledge) of **conflicting results**.

Don’t expect others to resolve your merge conflict!

# Process

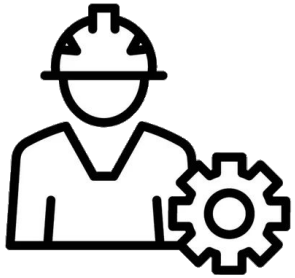
Merge conflicts (branches) are resolved by branch authors.

Expect **resolution** (knowledge) of **conflicting results**.

No premature optimizations.

**Focus** on **design validity** before scrutinizing artifacts.

# Science is a collaborative effort!

Software Engineering is a **collaborative effort**.
We should view science the same way!

# Science as Amateur Software Development


1. How can software engineering principles improve the rigor of data analyses?
2. Are these principles equally applicable to computational notebooks?
3. Describe three specific quality control mechanisms.
4. McElreath attributes a significant number of incorrect (scientific) studies to “sloth”. What are the specific issues he is calling out, and what solutions does he propose?
5. Provide an argument for why or why not general-purpose programming languages such as Python are an adequate choice for data analysis.

# Two example studies

# An example study: design

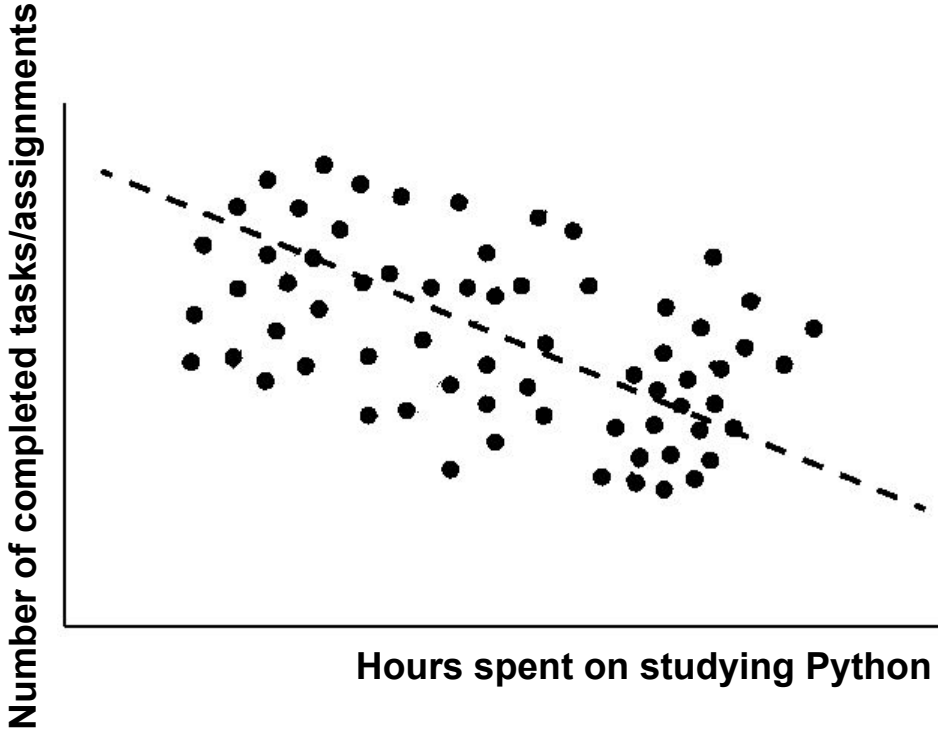
**Goal:**

Studying the **relationship** between **time spent** on **studying** Python and **success rate** in completing coding assignments.

**Methodology:**

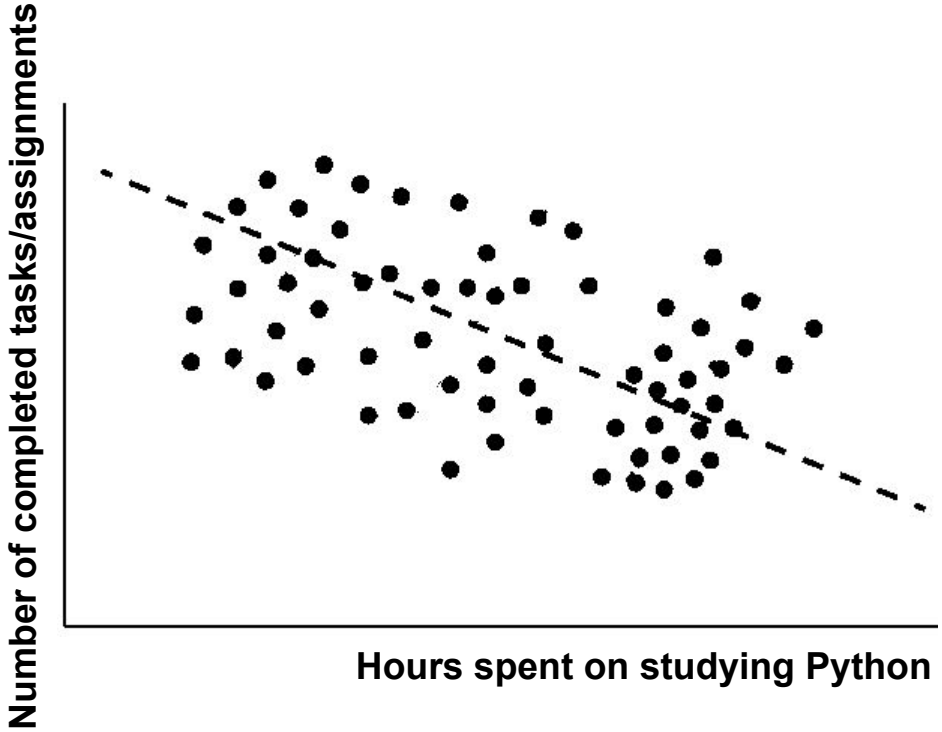
- ~100 participants are randomly selected in front of CSE.
- Each participant is given a high-level overview of the study.
- Each participant decides on how long to study before attempting to solve any coding assignment.
- Each participant solves as many coding assignments as possible in one hour (after studying).

# An example study: conclusions




Conclusion: Spending more time on learning Python makes you a worse Python programmer.

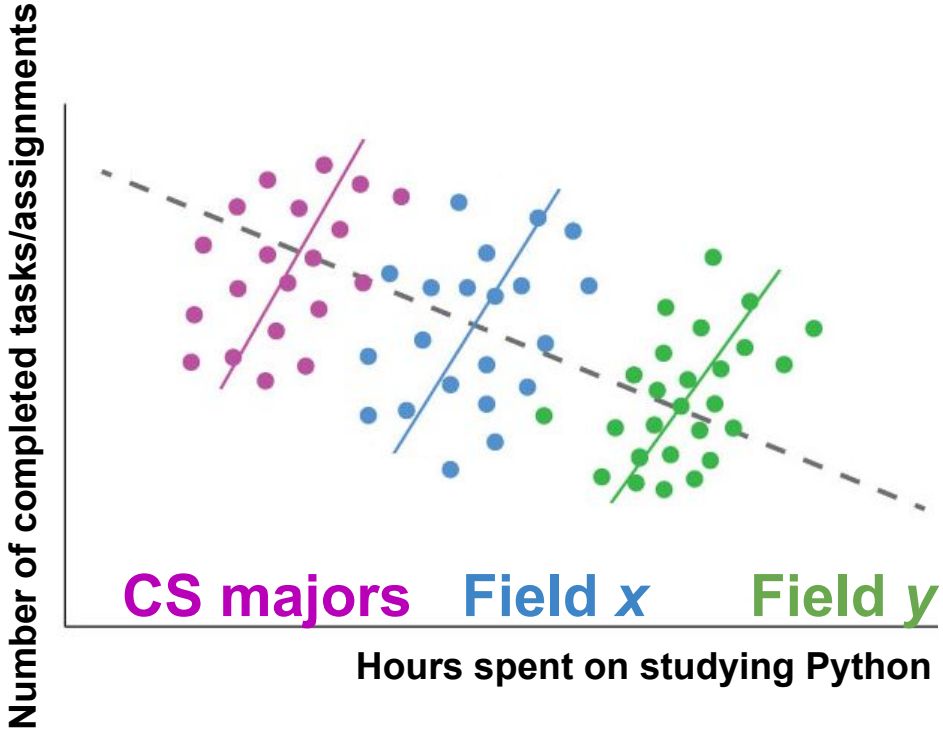
# An example study: conclusions




**What may cause this result?**

Conclusion: Spending more time on learning Python makes you a worse Python programmer.

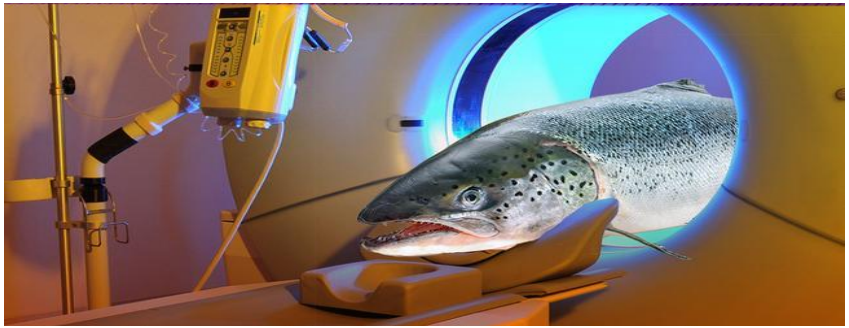
# An example study: Simpson's paradox




**Where did this study fail?**

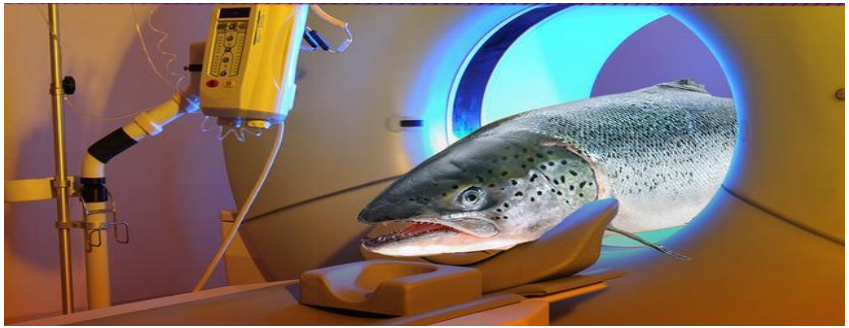
This phenomenon is called: **Simpson's paradox.**

# Another example study



http://www.prefrontal.org/files/posters/Bennett-Salmon-2009.pdf

# Another example study: design



**Neural correlates of interspecies perspective taking in the post-mortem Atlantic Salmon: An argument for multiple comparisons correction**

Craig M. Bennett[1], Abigail A. Baird[2], Michael B. Miller[1], and George L. Wolford[3]
[1] Psychology Department, University of California Santa Barbara, Santa Barbara, CA; [2] Department of Psychology, Vassar College, Poughkeepsie, NY; [3] Department of Psychological & Brain Sciences, Dartmouth College, Hanover, NH

## INTRODUCTION

With the extreme dimensionality of functional neuroimaging data comes extreme risk for false positives. Across the 130,000 voxels in a typical fMRI volume the probability of a false positive is almost certain. Correction for multiple comparisons should be completed with these datasets, but is often ignored by investigators. To illustrate the magnitude of the problem we carried out a real experiment that demonstrates the danger of not correcting for chance properly.

## METHODS

Subject. One mature Atlantic Salmon (Salmo salar) participated in the fMRI study. The salmon was approximately 18 inches long, weighed 3.8 lbs, and was not alive at the time of scanning.

Task. The task administered to the salmon involved completing an open-ended mentalizing task. The salmon was shown a series of photographs depicting human individuals in social situations with a specified emotional valence. The salmon was asked to determine what emotion the individual in the photo must have been experiencing.

Design. Stimuli were presented in a block design with each photo presented for 10 seconds followed by 12 seconds of rest. A total of 15 photos were displayed. Total scan time was 5.5 minutes.

Preprocessing. Image processing was completed using SPM2. Preprocessing steps for the functional imaging data included a 6-parameter rigid-body affine realignment of the fMRI timeseries, coregistration of the data to a $T_1$-weighted anatomical image, and 8 mm full-width at half-maximum (FWHM) Gaussian smoothing.

Analysis. Voxelwise statistics on the salmon data were calculated through an ordinary least-squares estimation of the general linear model (GLM). Predictors of the hemodynamic response were modeled by a boxcar function convolved with a canonical hemodynamic response. A temporal high pass filter of 128 seconds was include to account for low frequency drift. No autocorrelation correction was applied.

Voxel Selection. Two methods were used for the correction of multiple comparisons in the fMRI results. The first method controlled the overall false discovery rate (FDR) and was based on a method defined by Benjamini and Hochberg (1995). The second method controlled the overall familywise error rate (FWER) through the use of Gaussian random field theory. This was done using algorithms originally devised by Friston et al. (1994).

## DISCUSSION

Can we conclude from this data that the salmon is engaging in the perspective-taking task? Certainly not. What we can determine is that random noise in the EPI timeseries may yield spurious results if multiple comparisons are not controlled for. Adaptive methods for controlling the FDR and FWER are excellent options and are widely available in all major fMRI analysis packages. We argue that relying on standard statistical thresholds ($p < 0.001$) and low minimum cluster sizes ($k > 8$) is an ineffective control for multiple comparisons. We further argue that the vast majority of fMRI studies should be utilizing multiple comparisons correction as standard practice in the computation of their statistics.

## REFERENCES

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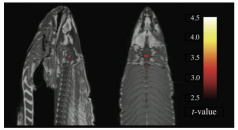
## GLM RESULTS

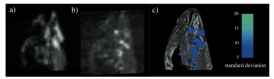



A *t*-contrast was used to test for regions with significant BOLD signal change during the photo condition compared to rest. The parameters for this comparison were $t(131) > 3.15$, p(uncorrected) $< 0.001$, 3 voxel extent threshold.

Several active voxels were discovered in a cluster located within the salmon's brain cavity (Figure 1, see above). The size of this cluster was 81 $mm^3$ with a cluster-level significance of $p = 0.001$. Due to the coarse resolution of the echo-planar image acquisition and the relatively small size of the salmon brain further discrimination between brain regions could not be completed. Out of a search volume of 8064 voxels a total of 16 voxels were significant.

Identical *t*-contrasts controlling the false discovery rate (FDR) and familywise error rate (FWER) were completed. These contrasts indicated no active voxels, even at relaxed statistical thresholds ($p = 0.25$).

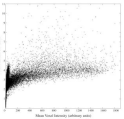
## VOXELWISE VARIABILITY




To examine the spatial configuration of false positives we completed a variability analysis of the fMRI timeseries. On a voxel-by-voxel basis we calculated the standard deviation of signal values across all 140 volumes.

We observed clustering of highly variable voxels into groups near areas of high voxel signal intensity. Figure 2a shows the mean EPI image for all 140 image volumes. Figure 2b shows the standard deviation values of each voxel. Figure 2c shows thresholded standard deviation values overlaid onto a high-resolution $T_1$-weighted image.

To investigate this effect in greater detail we conducted a Pearson correlation to examine the relationship between the signal in a voxel and its variability. There was a significant positive correlation between the mean voxel value and its variability over time ($r = 0.54$, $p < 0.001$). A scatterplot of mean voxel signal intensity against voxel standard deviation is presented to the right.



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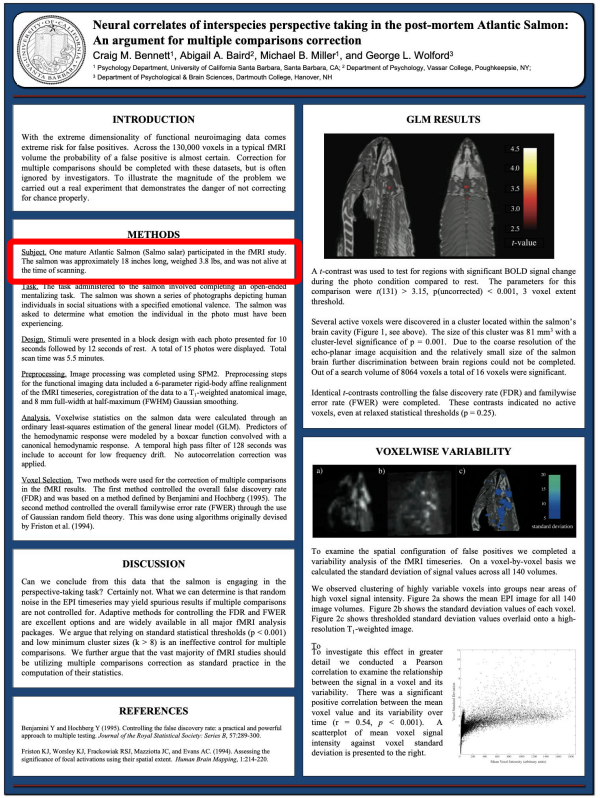
***Subject***: One mature **Atlantic Salmon** (Salmo salar) participated in the **fMRI study**. The salmon was approximately 18 inches long, weighed 3.8 lbs, and was **not alive at the time of scanning**.



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**INTRODUCTION**

With the extreme dimensionality of functional neuroimaging data comes extreme risk for false positives. Across the 130,000 voxels in a typical fMRI volume the probability of a false positive is almost certain. Correction for multiple comparisons should be completed with these datasets, but is often ignored by investigators. To illustrate the magnitude of the problem we carried out a real experiment that demonstrates the danger of not correcting for chance properly.

**METHODS**

Subject. One mature Atlantic Salmon (Salmo salar) participated in the fMRI study. The salmon was approximately 18 inches long, weighed 3.8 lbs, and was not alive at the time of scanning.

Task. The task administered to the salmon involved completing an open-ended mentalizing task. The salmon was shown a series of photographs depicting human individuals in social situations with a specified emotional valence. The salmon was asked to determine what emotion the individual in the photo must have been experiencing.

Design. Stimuli were presented in a block design with each photo presented for 10 seconds followed by 12 seconds of rest. A total of 15 photos were displayed. Total scan time was 5.5 minutes.

Preprocessing. Image processing was completed using SPM2. Preprocessing steps for the functional imaging data included a 6-parameter rigid-body affine realignment of the fMRI timeseries, coregistration of the data to a $T_1$-weighted anatomical image, and 8 mm full-width at half-maximum (FWHM) Gaussian smoothing.

Analysis. Voxelwise statistics on the salmon data were calculated through an ordinary least-squares estimation of the general linear model (GLM). Predictors of the hemodynamic response were modeled by a boxcar function convolved with a canonical hemodynamic response. A temporal high pass filter of 128 seconds was include to account for low frequency drift. No autocorrelation correction was applied.

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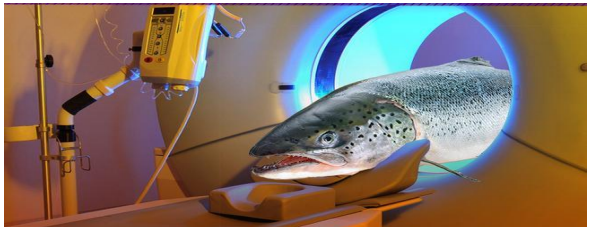
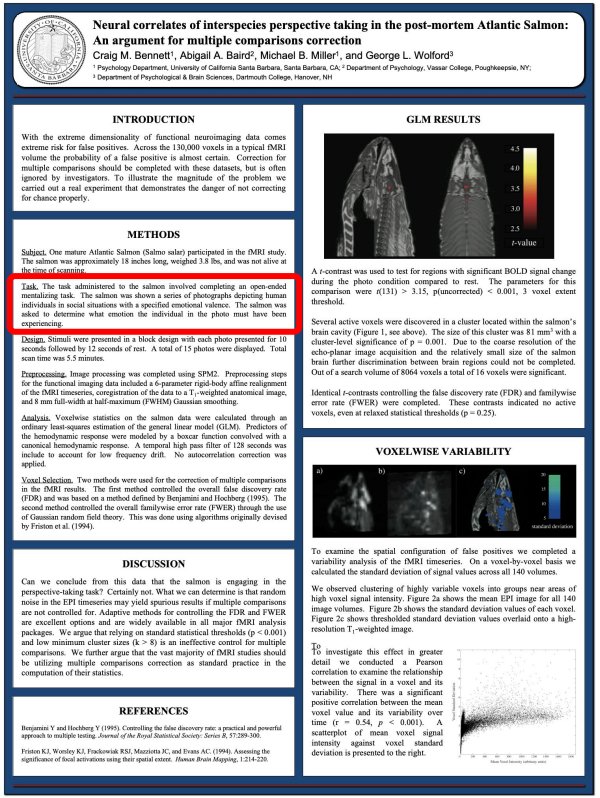
# Another example study: design

***Subject***: One mature **Atlantic Salmon** (Salmo salar) participated in the **fMRI study**. The salmon was approximately 18 inches long, weighed 3.8 lbs, and was **not alive at the time of scanning**.

***Task***: [...] **open-ended mentalizing task.** The salmon was **shown a series of photographs** depicting **human individuals in social situations** with a specified emotional valence. **The salmon was asked** to **determine** what **emotion** the **individual in the photo** must have been **experiencing**.





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**METHODS**

Subject. One mature Atlantic Salmon (Salmo salar) participated in the fMRI study. The salmon was approximately 18 inches long, weighed 3.8 lbs, and was not alive at the time of scanning.

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Design. Stimuli were presented in a block design with each photo presented for 10 seconds followed by 12 seconds of rest. A total of 15 photos were displayed. Total scan time was 5.5 minutes.

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# Another example study: conclusions

***Subject***: One mature **Atlantic Salmon** (Salmo salar) participated in the **fMRI study**. The salmon was approximately 18 inches long, weighed 3.8 lbs, and was **not alive at the time of scanning**.

***Task***: […] **open-ended mentalizing task.** The salmon was **shown a series of photographs** depicting **human individuals in social situations** with a specified emotional valence. **The salmon was asked** to **determine** what **emotion** the **individual in the photo** must have been **experiencing**.

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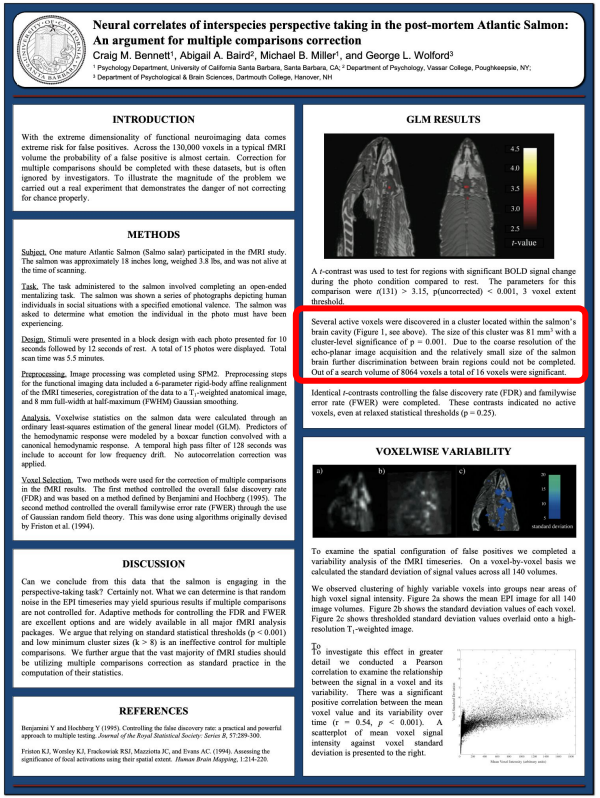

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METHODS

Subject. One mature Atlantic Salmon (Salmo salar) participated in the fMRI study. The salmon was approximately 18 inches long, weighed 3.8 lbs, and was not alive at the time of scanning.

Task. The task administered to the salmon involved completing an open-ended mentalizing task. The salmon was shown a series of photographs depicting human individuals in social situations with a specified emotional valence. The salmon was asked to determine what emotion the individual in the photo must have been experiencing.

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- Multiple hypotheses tested on the same data
- An argument for multiple comparisons correction

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- Clear **operationalization (implementation)?**
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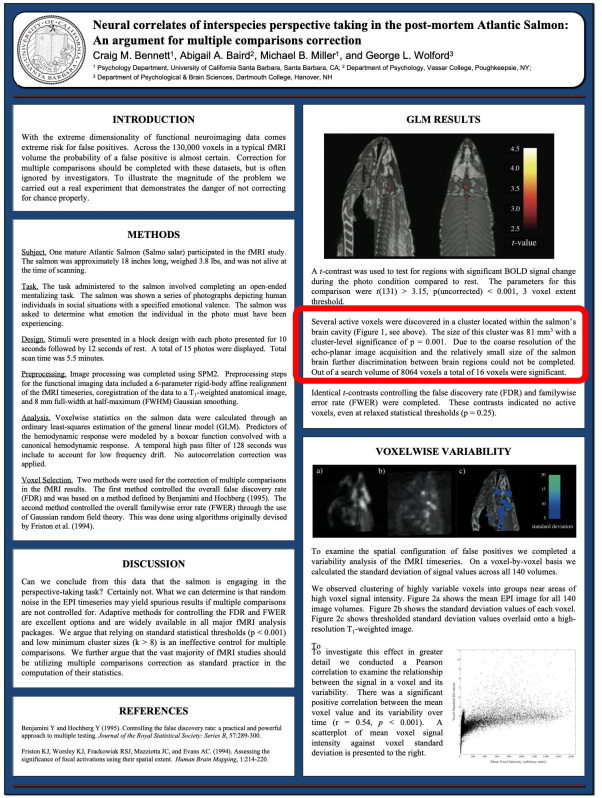

**Neural correlates of interspecies perspective taking in the post-mortem Atlantic Salmon: An argument for multiple comparisons correction**

Craig M. Bennett[1], Abigail A. Baird[2], Michael B. Miller[1], and George L. Wolford[3]

[1] Psychology Department, University of California Santa Barbara, Santa Barbara, CA; [2] Department of Psychology, Vassar College, Poughkeepsie, NY; [3] Department of Psychological & Brain Sciences, Dartmouth College, Hanover, NH

INTRODUCTION

With the extreme dimensionality of functional neuroimaging data comes extreme risk for false positives. Across the 130,000 voxels in a typical fMRI volume the probability of a false positive is almost certain. Correction for multiple comparisons should be completed with these datasets, but is often ignored by investigators. To illustrate the magnitude of the problem we carried out a real experiment that demonstrates the danger of not correcting for chance properly.

METHODS

Subject. One mature Atlantic Salmon (Salmo salar) participated in the fMRI study. The salmon was approximately 18 inches long, weighed 3.8 lbs, and was not alive at the time of scanning.

Task. The task administered to the salmon involved completing an open-ended mentalizing task. The salmon was shown a series of photographs depicting human individuals in social situations with a specified emotional valence. The salmon was asked to determine what emotion the individual in the photo must have been experiencing.

Design. Stimuli were presented in a block design with each photo presented for 10 seconds followed by 12 seconds of rest. A total of 15 photos were displayed. Total scan time was 5.5 minutes.

Preprocessing. Image processing was completed using SPM2. Preprocessing steps for the functional imaging data included a 6-parameter rigid-body affine realignment of the fMRI timeseries, coregistration of the data to a $T_1$-weighted anatomical image, and 8 mm full-width at half-maximum (FWHM) Gaussian smoothing.

Analysis. Voxelwise statistics on the salmon data were calculated through an ordinary least-squares estimation of the general linear model (GLM). Predictors of the hemodynamic response were modeled by a boxcar function convolved with a canonical hemodynamic response. A temporal high pass filter of 128 seconds was include to account for low frequency drift. No autocorrelation correction was applied.

Voxel Selection. Two methods were used for the correction of multiple comparisons in the fMRI results. The first method controlled the overall false discovery rate (FDR) and was based on a method defined by Benjamini and Hochberg (1995). The second method controlled the overall familywise error rate (FWER) through the use of Gaussian random field theory. This was done using algorithms originally devised by Friston et al. (1994).

DISCUSSION

Can we conclude from this data that the salmon is engaging in the perspective-taking task? Certainly not. What we can determine is that random noise in the EPI timeseries may yield spurious results if multiple comparisons are not controlled for. Adaptive methods for controlling the FDR and FWER are excellent options and are widely available in all major fMRI analysis packages. We argue that relying on standard statistical thresholds ($p < 0.001$) and low minimum cluster sizes ($k > 8$) is an ineffective control for multiple comparisons. We further argue that the vast majority of fMRI studies should be utilizing multiple comparisons correction as standard practice in the computation of their statistics.

REFERENCES

Benjamini Y and Hochberg Y (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society: Series B*, 57:289-300.

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GLM RESULTS

A *t*-contrast was used to test for regions with significant BOLD signal change during the photo condition compared to rest. The parameters for this comparison were $t(131) > 3.15$, p(uncorrected) $< 0.001$, 3 voxel extent threshold.

Several active voxels were discovered in a cluster located within the salmon's brain cavity (Figure 1, see above). The size of this cluster was 81 $mm^3$ with a cluster-level significance of $p = 0.001$. Due to the coarse resolution of the echo-planar image acquisition and the relatively small size of the salmon brain further discrimination between brain regions could not be completed. Out of a search volume of 8064 voxels a total of 16 voxels were significant.

Identical *t*-contrasts controlling the false discovery rate (FDR) and familywise error rate (FWER) were completed. These contrasts indicated no active voxels, even at relaxed statistical thresholds ($p = 0.25$).

VOXELWISE VARIABILITY

To examine the spatial configuration of false positives we completed a variability analysis of the fMRI timeseries. On a voxel-by-voxel basis we calculated the standard deviation of signal values across all 140 volumes.

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Where did this study fail (on purpose)?

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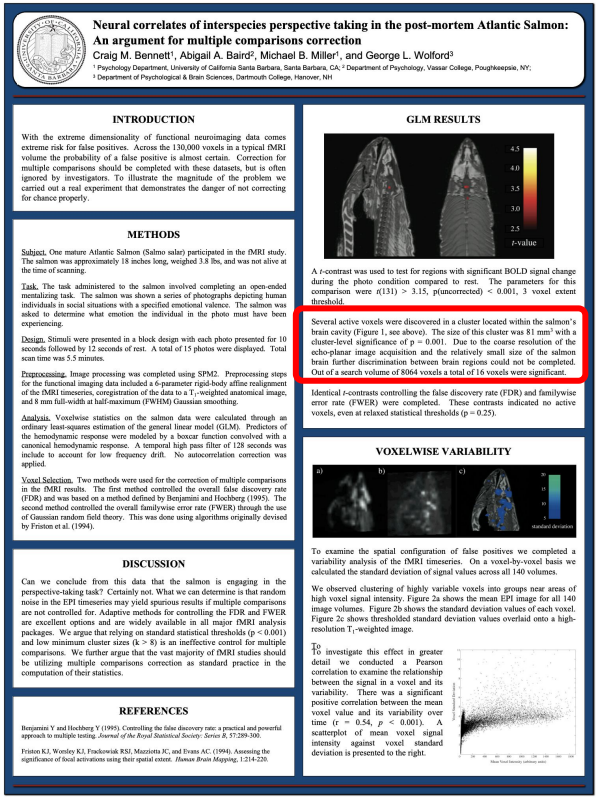

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Valid data analysis goes well beyond implementation correctness.