Automatic Classifiers as Scientific Instruments: One Step Further Away from Ground-Truth

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Machine learning to advance basic science

• Machine perception can advance basic science in:
  • Psychology
  • Education
  • Medicine

• ...by providing automatic classifiers as new scientific instruments, e.g.:
  • Automatic stress detectors from wrist monitors instead of questionnaires.
  • Facial action unit detectors from video instead of electromyography.
  • Student engagement detectors from video instead of observational protocols.
Suppose a researcher wishes to measure the relationship between two constructs $U$ and $V$, e.g.:

$U =$ stress

$V =$ academic performance.

Standard methodology:

- Use a **standard measurement tool** (e.g., survey, observational protocol) to estimate the values of $U$ and $V$ from a sample of $n$ participants.
- This produces two vectors $u, v \in \mathbb{R}^n$, which we can assume w.l.o.g. have 0-mean and 1-length.
- Estimate the correlation between $U$ and $V$ as:

$$ r = \rho(u, v) = u^\top v = \cos \angle(u, v) $$

Only the angle between the two vectors determines their correlation.
Correlation study

- But what if the researcher instead uses an automatic stress detector $d$ whose correlation with ground-truth measurements is $q$ (known from prior validation)?

- Instead of $u$, the researcher obtains a vector $\hat{u}$.

- What kind of spurious deductions about the correlation between $U$ and $V$ could result?
Trivariate correlation

- Suppose $u$ and $v$ are ground-truth values of $U$ and $V$.
- The correlation between $u$ and $v$ is $r = \cos(105^\circ) = -0.259$.  

Trivariate correlation

- Using a detector $d$, the researcher might obtain $\hat{u}$, whose correlation with $u$ is $q$.

- The correlation between $\hat{u}$ and $v$ is $\cos(135^\circ) = -.707$ — much larger than, but same sign as, the ground-truth correlation.
Trivariate correlation

- But they might also obtain vector $\hat{u}'$, whose correlation with $u$ is also $q$.

- The correlation between $\hat{u}'$ and $v$ is $\cos(75^\circ) = +.259$ — this is the **opposite sign** as the ground-truth correlation.

  We call this a **false correlation**.
Main results

1. The set of all vectors whose correlation with $u$ is $q$, is an $(n-3)$-sphere $\mathcal{T}^n \in \mathbb{R}^n$. 

2. If the correlation between $u$ and $v$ is $r$, then the expected sample correlation between $u$ and $v$, where $v$ is drawn uniformly at random from $\mathcal{T}$, is $qr$. 

3. We derive a formula $h(n, q, r)$ for the probability of a false correlation. 

4. We show that $h$ is monotonically decreasing in $q$ and $n$. 

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2. If the correlation between \( \mathbf{u} \) and \( \mathbf{v} \) is \( r \), then the expected sample correlation between \( \hat{\mathbf{u}} \) and \( \mathbf{v} \), where \( \hat{\mathbf{u}} \) is drawn uniformly at random from \( \mathcal{T}^n \), is \( qr \).
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3. We derive a formula \( h(n,q,r) \) for the probability of a false correlation.

4. We show that \( h \) is monotonically decreasing in \( q \) and \( n \). But it can still be non-negligible for values of \( n, q \) used in recent affective computing studies — despite a small p-value.
Case study: Student engagement vs. cognitive task performance

- Whitehill et al. 2014 measured student engagement using (1) observational protocol and (2) automatic engagement detector $d$ ($q=0.50$).
- Using hand-coded labels, $\text{corr}(U, V)$ was estimated as $r=0.37$.
- Given $n$, $q$, $r$, what is probability of false correlation from $d$?
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\[ U: \text{Engagement} \]
\[ V: \text{Cognitive task performance} \]

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Probability of "false negative" correlation \((q = 0.5, r = 0.37)\)

Probability vs. \( n \):
- Probability decreases as \( n \) increases.