Sensory substitution can improve decision-making

Heinrich Peters *, Sandra C. Matz, Moran Cerf

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How do we make consequential decisions?

- People frequently make consequential decisions based on abstract, numerical information
  - Performance metrics → investing/lending
- Human decision-making (x) → numerical data → nonlinear relationship and interactions

Use of sensory substitution to improve decision-making based on quantitative data

Sensory substitution and intuitive decision-making

- **Sensory substitution:**
  - Encoding information → a sensory modality → not involved in the processing of such information
    - camera information → vibro-tactile / auditory information → wearable vibro-tactile

- **Explicit rule abstraction → Configural learning**
  - rather deliberately inferring decision rules → intuitive, perceptual strategies
  - **Explicit rule abstraction** → tabular numerical data / make predictions → for additive, linear cue environments, but not nonlinear relationships
  - **Configural learning** → implicit, intuitive process that is better suited to learn holistic representations rather than individual cues (Enkvist et al., 2006; Olsson et al., 2006).
    - Deviate from rationality? →accurate in nonlinear cue environments/ more aligned with expected utility theory in many perceptual or motor decision tasks

Theoretical Background and Current Research

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Existing Literature

- Explored a wide range of applications for tactile sensory substitution
- Configural learning and intuition play an important role in sensory substitution
- Sensory substitution taps into implicit, intuitive, learning processes similar to those underlying configural learning

Research Gap

- Link sensory substitution to decision-making (transfer information from one sensory modality to another)
- Performance improved? Shifting from explicit rule abstraction to configural learning

Research Aim

- Configural learning might lead to improved performance when decision-makers are required to integrate complex (and interactive) information from multiple sources
- Sensory substitution can enable people to experience abstract information more holistically, thereby encouraging configural learning and intuitive decision-making.

Research Question 1: Can sensory substitution improve decision-making?

Hypothesis: Displaying data in the form of tactile in formation (i.e., sensory substitution), rather than in numerical form, will result in higher decision-making accuracy.

Research Question 2: Which underlying mechanism explains the effect?

Hypothesis: The benefit of sensory substitution is the result of a shift from (deliberate) explicit rule abstraction to (intuitive) configural learning.

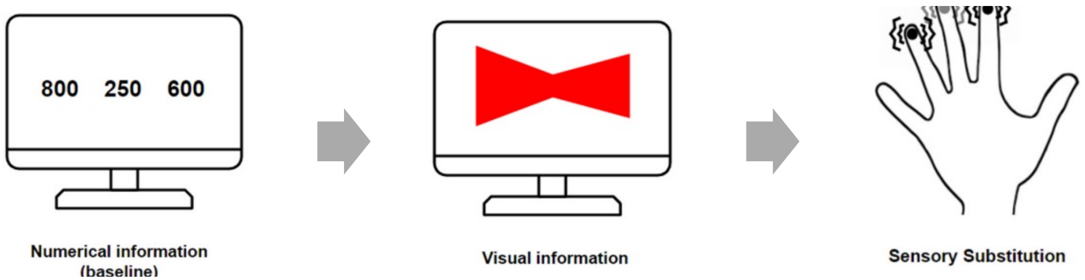
Methodology

- One-factorial within-person design with three randomly ordered counterbalanced conditions
- Multiple-cue prediction tasks → repeatedly make binary decisions
- Make a prediction regarding the value of the unknown outcome variable → the left or the right arrow key on a computer keyboard
- Receive feedback
- Each condition involved 100 trails
- Scikit-Learn (Pedregosa et al., 2011) “make_classification” method to generate random n-class classification problems

Participants: 44 (22.04 ± 2.71 years old, 66.66% female)

- Age, gender, and handedness
- No practice (baseline)
- $5 for participation, 20¢ for correct answer

Condition 1: Numerical Baseline
Condition 2: Visual exemplar (whether configural learning is part of the cognitive mechanism)
Condition 3: Sensory Substitution



1) abstract numerical information (three integer numbers predictive of a single binary outcome)

2) abstract visual exemplars (shapes that represent those same three integers),

3) sensory substitution (vibrations administered through a vibro-tactile interface representing those same three integers).

Outcome measures and statistical hypotheses

The percentage of correct trials in each of the three conditions

$$P_t = 0.01\left[\left(\sum_{0}^{t} C_t\right) - tp\right] + p$$

- Pt denotes the learning state in trial t
- Ct denotes the value of the participant's response in trial t,
- p denotes the chance of guessing the correct answer (i.e., the expected value of the target variable).
- The 0.01 constant was chosen to ensure a [0, 1] range for P across the 100 trials.
- A final value of 0 reflects a participant who made the wrong prediction in every single trial and a final value of 1 reflects perfect predictions across all trials.
- A final value of 0.5 reflects chance performance.

1. No statistical difference in accuracy between the sensory substitution condition
2. Response times in the sensory substitution condition and the visual exemplar condition are significantly shorter than in the numerical condition,
3. Participants reported higher degrees of intuitive decision-making in the sensory substitution condition and the visual exemplar condition compared to the numerical baseline condition.
4. Based on the idea that configural learning is well suited for nonlinear cue environments (Juslin et al., 2008) → partici-pants' responses in the sensory substitution condition were better explained by a nonlinear cognitive model compared to a linear one (Brehmer & Brehmer, 1988)

Results

Research question 1: Can sensory substitution improve decision-making?

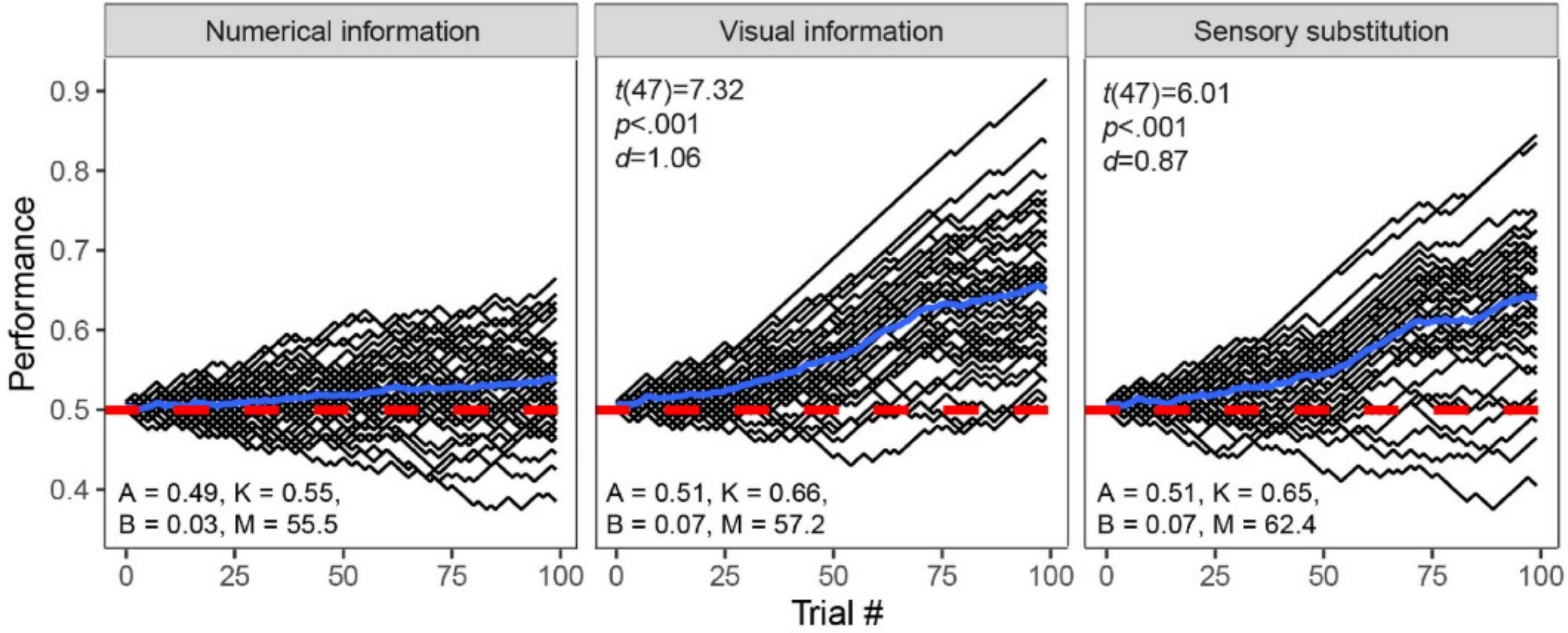


Fig. 2. Decision-making performance over time. Performance curves are depicted in gray (individual) and blue (mean) lines. Dashed red lines denote chance performance. The statistics in the upper left corner show the comparison of the visual exemplar and sensory substitution conditions with the numeric baseline condition. The parameters of the estimated generalized logistic function are shown on the bottom left.

Results

Research question 2: Which underlying mechanism explains the effect?

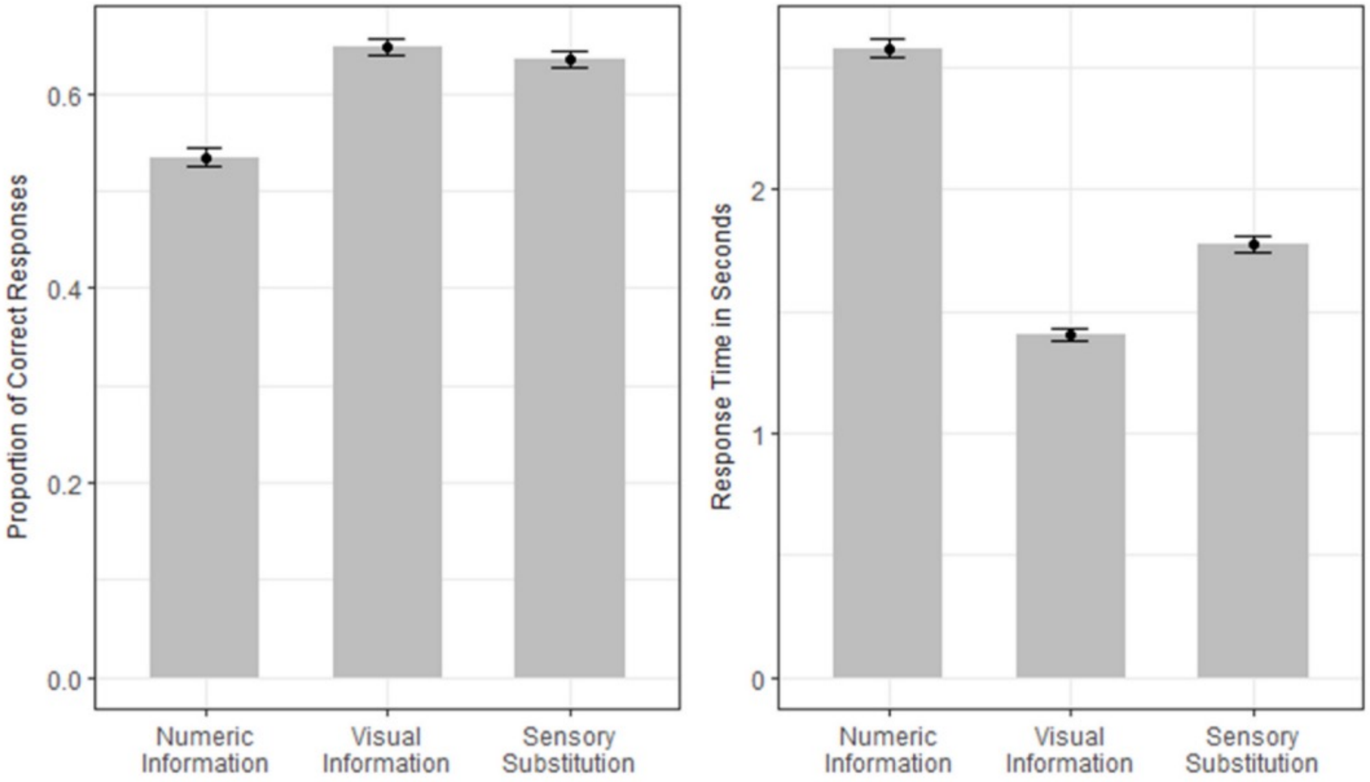


Fig. 3. Comparison of decision-making performance and response times across conditions. Mean proportion of correct responses per user across conditions (left). Mean response time in seconds across conditions (right). Error bars represent standard errors for repeated measures comparison.

- **Comparison of sensory substitution and visual exemplar condition**
  - the same configural learning benefits → not observe any differences in accuracy
  - similar performance trajectories → no difference in the growth rate
- **Response time**
  - Participants in the sensory substitution condition and the visual exemplar condition were significantly faster in their response time
  - suggestion that configural learning should be less time-intensive than explicit rule abstraction
- **Intuitiveness ratings**
  - more intuitive compared to the numerical baseline condition
  - no difference in participants' subjective intuitiveness b/w visual and sensory substitution

Results

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Cognitive Model

- Explicit rule abstraction → linear solution strategies / Configural learning → interactive cue environments
- linear additive regression model → explicit rule abstraction / A model containing interaction effects → configural learning
  - the performance of the nonlinear interaction model > linear baseline model → configural learning

- Configural learning scores were operationalized as the difference in model fit between a linear model without interactions and a model with interactions

$$Linear\ model: logit(p_t) = \beta_0 + \beta_1 c_{1t} + \beta_2 c_{2t} + \beta_3 c_{3t} + e_t$$

$$Interaction\ model: logit(p_t) = \beta_0 + \beta_1 c_{1t} + \beta_2 c_{2t} + \beta_3 c_{3t} + \beta_4 c_{1t} c_{2t} + \beta_5 c_{1t} c_{3t} + \beta_6 c_{2t} c_{3t} + e_t$$

  - where pt = E [Rt |c1t, c2t, c3t] and Rt represents the binary response variable
  - c1t, c2t, and c3t represent the cues on which each decision was based.
- Configural learning scores → higher when participants used nonlinear cue integration strategies and lower when participants used linear cue integration strategies
- Pairwise dependent sample t-tests:
  - configural learning scores in the sensory substitution / visual condition is significantly higher
  - visual exemplar condition were also significantly higher than in the sensory substitution condition

Performance difference → associated with a shift from explicit rule abstraction to configural learning

Discussion

- The significant performance improvement:
  - **sensory substitution / visual exemplar** compared to the **numerical baseline condition**

- No significant performance difference was found between the sensory substitution and the visual exemplar condition (configural learning as the mechanism underlying the performance increase)
  - participants in both the sensory substitution and visual exemplar conditions showed significantly lower response times compared to the numerical baseline condition.

- Both sensory substitution and visual exemplar tasks were rated by participants as significantly more intuitive compared to the numerical baseline task
  - Cognitive modelling analysis indicates that participants relied more heavily on configural learning

- **The benefits afforded by sensory substitution are the result of a shift from (deliberate) explicit rule abstraction to (intuitive) configural learning**

Discussion

- **The application of sensory substitution in decision making was explored:**
  - the first to test the effects of sensory substitution in the field of decision making
  - Previous studies have focused on the development and application areas of sensory substitution techniques → provides new perspectives and possibilities
- **Revealing the positive effects of sensory substitution on decision making:**
  - this study found that sensory substitution can improve decision making
  - By projecting data into tactile perceptual modalities, people can more intuitively feel the solutions to complex problems, rather than just inferring them through cognitive reasoning
- **Suggested research directions for mechanisms and boundary conditions of sensory substitution:**
  - this study also suggests directions for further research on mechanisms and boundary conditions of sensory substitution effects.
  - Future research could investigate the neural mechanisms of sensory substitution effects and the moderating role of specific data attributes and level of training on sensory substitution effects through neuroscientific approaches.

Limitation and Future Direction

- **Initial evidence for the proposed role of configural learning in sensory-based decisions**
  - further investigate the mechanism underlying the performance improvement
  - the neural underpinnings of the effect using brain readouts such as EEG data to try to distinguish the neural pathways associated with explicit rule abstraction and configural learning
- **Demonstrates a strong positive effect of sensory substitution in a well-controlled context**
  - how the results generalize to more complex use-cases beyond artificially generated data with specific properties (3 features)
  - A simpler version of a sensory device imposes bounds on the generalizability to more complex use cases
- **Study how a system like the vibro-tactile interface can be turned into practical applications in ecological settings**
  - how sensory substitution interacts with existing knowledge in a decision domain: would the effect persist when people interpret the predictors in meaningful ways and build on prior knowledge when making decisions?

The University of Melbourne (Australian University)
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