**Preregistration**

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### Study Information

1. Title  
   Kinematic readout of confidence in collective decision-making
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3. Description  
   Research on collective decision-making has shown that groups can outperform their best individual members through “confidence sharing”: individuals communicate how confident they feel in their individual judgements so as to arrive at a collective decision [1]. However, such explicit communication of confidence estimates can be noisy, biased, and cognitively demanding [2,3]. Yet, replacing interpersonal communication by simple heuristics also comes with difficulties [3]. In the present study, we investigate an alternative, implicit way of confidence sharing. We test the hypothesis that, in the absence of explicit communication, two individuals can infer each other’s subjective confidence through simple action observation [4,5], and in this way achieve a group benefit. To this end, we ask two participants (A and B) to solve a 2AFC perceptual task, with individual decisions being followed by a collective decision. Participants express their decisions by aiming for one of two targets [5], while movement kinematics are recorded. In each trial, participant A (B) aims for one of the two targets, then observes participant B (A) also aiming for one of the two targets, and then makes the collective decision. We predict that participants will read out confidence from each other’s movements and incorporate this inferred confidence in the collective decision-making process. The findings of the present study will provide novel insights into how action observation can inform collective decision-making.
4. Hypotheses
   1. Collective benefit: If participants can infer confidence from movement kinematics, then they should be able to achieve a collective benefit. The collective benefit hypothesis can take two forms. In the stronger form, the perceptual sensitivity of the dyad is higher than the perceptual sensitivity of the more sensitive individual of the dyad (as defined in [1]). In the weaker form, the perceptual sensitivity of the dyad is higher than the perceptual sensitivity of the less sensitive individual of the dyad and thus only the less sensitive individual achieves a benefit. This would extend the findings by Bahrami et al. on collective benefits in perceptual decision-making [e.g., 1-3] by demonstrating confidence sharing through movement kinematics.
   2. Confidence encoding: If confidence is “encoded” in people’s movements, then the kinematics of participants’ aiming movements will vary as a function of how confident they feel in their decisions. Thus, we will be able to predict participants’ confidence based on variations in movement kinematics on the single-subject, single-trial level, using regression models [see 6 and 7].
   3. Single-trial confidence readout predicts collective decisions: We hypothesize that, at the single-trial level, the collective decision will depend on  
      i) the individual decisions of the two participants (agent 1 and 2\*),  
      ii) the individual confidence of agent 1 in that trial,  
      iii) the confidence information encoded in the movement kinematics of agent 2 in that trial.  
      \*Note that agent 1 refers to the participant who is responsible, in a given trial, for taking the collective decision. In each trial, the order of decisions is such that agent 1 takes her individual decision, then agent 1 observes agent 2’s individual decision, and finally agent 1 takes the collective decision [see 8.1].

### Design Plan

1. Study type: Experiment
2. Blinding
   1. No blinding is involved in this study.
3. Is there any additional blinding in this study? No.
4. Study design
   1. In this experiment, two participants (“agent blue” and “agent yellow”) take part together, as a dyad. The two participants perform a 2AFC perceptual task where they have to detect an oddball (a grating with higher contrast) in one of two stimulus intervals. Thus, on each trial, the task is to make a decision between 1st interval and 2nd interval. Each participant first takes this decision individually. After that, participants are asked to provide a group/collective decision.  
      The experiment is structured in two blocks with 80 trials each; the total number of trials is 160. Each trial consists of three consecutive decisions: one individual decision taken by agent blue, one individual decision taken by agent yellow, and one group decision (taken by either agent blue or agent yellow). The two agents alternate who takes the first individual decision on a trial-by-trial basis. The agent who takes the first decision is always the same that takes the group decision in the end.
   2. As independent variables, **Decision type**, **Task difficulty** and **Target interval** are varied. Decision type refers to whether the decision is taken by each participant individually or by both participants collectively (individual vs. group decision). Task difficulty refers to the contrast of the oddball stimulus (“target contrast”) that participants are asked to detect. There are four target contrasts (11.5%, 13.5%, 17%, 25%); the variable thus has four levels. Target interval refers to whether the oddball stimulus occurs in the first or second of two sequential stimulus intervals; the variable thus has two levels (first, second). This results in eight different contrast/interval combinations.
5. Randomization
   1. The target contrast and interval are randomized across trials, with the following constraints: Each contrast appears equally often per interval. Each contrast/interval combination appears equally often per agent in the role of the group decision-maker. These constraints hold separately for each block.
   2. Participants will be randomly assigned to act as blue agent (seated on the left) and yellow agent (seated on the right), respectively. The colors merely serve to facilitate the turn-taking procedure such that, at the beginning of each trial, the agent who starts is announced on the screen. The colors are also used when the individual decisions are declared on the screen, such that participants are informed about each other’s decision.

### Sampling Plan

1. Existing data
   1. Registration prior to creation of data: As of the date of submission of this research plan for preregistration, the data have not yet been collected, created, or realized.
2. Explanation of existing data: We ran a pilot version of the experiment to calibrate task difficulty and task duration.
3. Data collection procedures
   1. Participants will be recruited from the participant pool of the Istituto Italiano di Tecnologia (IIT) in Genova, Italy. Inclusion criteria are: aged between 18 and 40 years, normal or corrected-to-normal vision, right-handed, Italian-speaker, no neurological or psychiatric disease history. Participants will be paid 15 EUR per hour. For each experimental session, two individuals will be invited to participate together as a dyad. Dyad members will not know each other. Dyads will be composed of same-sex individuals, i.e., there will be female-female and male-male dyads.
4. Sample size
   1. Our target sample size is 15 dyads, i.e., 30 participants.
5. Sample size rationale
   1. We determined our sample size based on previous studies (see 14.2) which used the same perceptual discrimination task to investigate collective decision-making, just as in the present study. One of our main measures of interest adopted from previous studies is the so-called “collective benefit” (see 18.2), an index of whether two individuals perform better together than each of them on their own. This measure has been reliably analyzed with the chosen sample size.
   2. Previous studies with the same sample size (in order of publication):  
      Bahrami, B., Olsen, K., Latham, P. E., Roepstorff, A., Rees, G., & Frith, C. D. (2010). Optimally interacting minds. *Science, 329*(5995), 1081-1085.  
      Bahrami, B., Olsen, K., Bang, D., Roepstorff, A., Rees, G., & Frith, C. (2012). Together, slowly but surely: the role of social interaction and feedback on the build-up of benefit in collective decision-making. *Journal of Experimental Psychology: Human Perception and Performance, 38*(1), 3.  
      Bahrami, B., Olsen, K., Bang, D., Roepstorff, A., Rees, G., & Frith, C. (2012). What failure in collective decision-making tells us about metacognition. *Philosophical Transactions of the Royal Society B: Biological Sciences, 367*(1594), 1350-1365.  
      Bang, D., Aitchison, L., Moran, R., Herce Castanon, S., Rafiee, B., Mahmoodi, A., ... & Summerfield, C. (2017). Confidence matching in group decision-making. *Nature Human Behaviour, 1*(6), 0117.
6. Stopping rule: n.a.

### Variables

1. Manipulated variables
   1. See section 8.2.
2. Measured variables
   1. We will collect and analyze the following outcome measures:
      1. **Decision outcome** (two-alternative forced choice; response options are “1st interval” and “2nd interval”)
      2. **Confidence rating** per decision, rated on scale from 1 to 6, with 1 meaning very little confidence and 6 meaning very high confidence. Participants provide a confidence rating after every decision, in response to the question “How sure are you?”.
      3. **Perceptual sensitivity** (see section 18)
      4. **Collective benefit** (see section 18)
      5. **Kinematic variables** (wrist height, wrist velocity, wrist acceleration, etc.) to characterize participants’ aiming movements. These variables will be extracted by tracking participants’ movements with a near-infrared motion capture system with optical cameras.
      6. **Reaction time**: time interval between decision prompt and initial movement onset, defined as the point when a predefined velocity threshold has been passed
      7. **Deliberation time**: time interval between initial movement onset and start of the aiming movement
      8. **Movement time**: time interval between start of the aiming movement and the target button press
      9. **Agreement/disagreement**: indicates whether participants agreed in their individual decisions or not
      10. **Change of mind**: indicates whether the agent who takes the collective decision, in a particular trial, keeps with her prior individual decision (e.g., interval 1) or changes her mind and chooses the alternative option (e.g., interval 2)
      11. **Questionnaire scores**: Interpersonal Reactivity Index (IRI; Davis, 1980) and Autism Spectrum Quotient (AQ; Baron-Cohen, 2001)
      12. **Open-ended questions** (asked after the collective decision-making task):
          1. (1) How confident would you rate yourself in this task?
          2. (2) How confident would you rate your partner in this task?
          3. (3) How competent would you rate yourself in this task?
          4. (4) How competent would you rate your partner in this task?
          5. (5) Did you try to infer how sure your partner was in her decisions? If so: how?
          6. (6) Do you have any further comments?
   2. As predictors/covariates, we will include:
      1. **Individual perceptual sensitivity**: Following Bahrami et al., we predict that the similarity of dyad members’ perceptual sensitivity will affect the extent to which that dyad will achieve a collective benefit. If dyad members’ individual sensitivities are too different from each other, then no collective benefit can be achieved. Thus, we expect a correlation between collective benefit and relative sensitivity (see [1]).
3. Indices
   1. To measure participants’ “perceptual sensitivity” in the 2AFC perceptual task, we construct a psychometric curve by plotting the proportion of trials in which the oddball was seen in the 2nd interval against the contrast difference at the oddball location. The slope of the curve (s) is taken as indicator of perceptual sensitivity.
   2. We measure the “collective benefit” in the strong form in terms of the ratio between the perceptual sensitivity of the dyad and that of the better (i.e., more sensitive) individual (sdyad/smax). Two individuals achieve a collective benefit if: sdyad/smax > 1. That is, a collective benefit is achieved if the dyad performs better (is more sensitive) than the better (more sensitive) individual (see [1]).
      1. In addition, we measure the “collective benefit” in the weaker form by computing the ratio between the perceptual sensitivity of the dyad and that of each dyad member. This means that we compute one value for the blue agent (sdyad/sAgentBlue) and one value for the yellow agent (sdyad/sAgentYellow), where sdyad is computed here based on only those group decisions taken by the respective agent (blue or yellow) and sAgent is computed as the respective agent’s individual sensitivity. This way, we test whether each agent benefits individually from the collective action.

### Analysis Plan

1. Statistical models
   1. To test whether participants reach a **collective benefit** (hypothesis 4.1), we will perform a paired t-test, comparing the perceptual sensitivity (i.e., the slope of the psychometric function, see 18.1) of the dyad with the perceptual sensitivity of the more/less sensitive individual, in line with [1-3, 9].
   2. To test hypothesis 4.2, we will use regression models to quantify **confidence encoding** at the single-subject, single-trial level (see [7]).
   3. To test hypothesis 4.3, we will build regression models that **predict the collective decision** on a given trial based on the decision and confidence of agent 1 in that trial, the decision of agent 2 in that trial, and the confidence information encoded in the movement kinematics of agent 2 in that trial. Models will be trained separately for each participant.
2. Transformations (optional)
3. Inference criteria (optional)
   1. We will use the standard p<.05 criteria for determining if the ANOVA and the post hoc test suggest that the results are significantly different from those expected if the null hypothesis were correct. If needed, we will adjust post hoc tests for multiple comparisons.
4. Data exclusion
   1. Data of a particular dyad will not be included in the analysis in the following cases.
      1. If severe technical error occurs with the motion capture recording such that kinematics are not recorded/saved properly.
      2. If participants do not comply to the behavioral instructions, e.g., by systematically moving before the decision prompt is displayed or by constantly using the same value on the confidence scale or the same decision button.
      3. If participants do not complete the experiment.
5. Missing data
6. Exploratory analysis (optional)
   1. Following Bahrami et al. [9], we consider performing a sliding window analysis to assess the temporal development of the collective benefit throughout the experiment.
   2. Following Mahmoodi et al. [10], we consider performing additional analyses focusing on the comparison between the more and less sensitive member of each dyad, to assess whether individual perceptual sensitivity (relative to the partner) plays a role.

### References

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