Title:

Social influence protects collective decision making from equality bias

Authors:

Uri Hertz[1]*,

Margaux Romand-Monnier[1],

Konstantina Kyriakopoulou[1],

Bahador Bahrami[1]

Affiliations:

[1]UCL Institute of Cognitive Neuroscience, 17 Queen Square, London WC1N 3AR, UK

*Correspondence to: Uri Hertz, u.hertz@ucl.ac.uk, +44 2076795429, UCL Institute of Cognitive Neuroscience, 17 Queen Square, London WC1N 3AR, UK

Abstract

A basic tenet of research on wisdom of the crowds – and key assumption of Condorcet's Jury Theorem – is the independence of voters' opinions before votes are aggregated. However, we often look for others' opinions *before* casting our vote. Such social influence can push groups towards herding, leading to "madness of the crowds". To investigate the role of social influence in joint decision making, we had dyads of participants perform a visual odd-ball search task together. In the Independent (IND) condition participants initially made a private decision. If disagreeing, discussion and collective decision ensued. In the Influence (INF) condition no private decisions were made and collective decision was immediately negotiated. Dyads that did not accrue collective benefit under IND condition improved with added social influence under INF condition. In Experiment 2, covertly, we added noise to one of the dyad members' visual search display. The resulting increased heterogeneity in dyad members' performances impaired the dyadic performance under IND condition (Bahrami et al., 2010). Importantly, dyadic performance improved with social influence under INF, replicating Experiment 1. Further analyses revealed that under IND condition, dyads exercised equality bias (Mahmoodi et al., 2015) by granting undue credit to the less reliable partner. Under INF condition, however, the more reliable partner (correctly) dominated the joint decisions. While social influence may impede collective success under ideal conditions, our results demonstrate how it can help the group members overcome factors such as equality bias, which could potentially lead to catastrophic failure.

Key Words:

Social Influence, Wisdom of the Crowds, Social Psychology, Collective Decision Making

Introduction

Independently generated opinions of many lay individuals, if put together properly, can outperform experts (Condorcet, 1785; Jolyon J. Faria, Codling, Dyer, Trillmich, & Krause, 2009; Galton, 1907; Surowiecki, 2005). Such "wisdom of the crowd" depends critically on independence of individual votes, the competence of voters, and an appropriate aggregation schemes (Bates & Granger, 1969; Galton, 1907; Kerr & Tindale, 2011; Koriat, 2012). For example, the mean of economic forecasts made by independent individuals is typically more accurate than the forecast of the crowd's average member (Zarnowitz, 1984).

However, in everyday life, we often prefer to hear others' opinions before casting our vote. This may prove a beneficial strategy, for example when information is not equally available to all group members and discussion can promote fact finding and problem solving of groups (Abrahamson, 1991; Blinder & Morgan, 2000; Ehrmann & Stinson, 1999; Karl, Susskind, & Wallace, 2007). Individuals can accrue benefits from the opinions of others through social and observational learning (Bandura, 1977) and increase their accuracy (Farrell, 2011; Soll & Larrick, 2009; Yaniv, 2004). In animal behaviour, groups of many inaccurate individuals (many-wrong) can produce accurate group decisions in a distributed and decentralized way through social influence, a phenomenon also known as swarm intelligence (Bazazi et al., 2010; Berdahl, Torney, Ioannou, Faria, & Couzin, 2013; Bonabeau, Dorigo, & Theraulaz, 1999; Clark & Mangel, 1984).

But social influence can have catastrophic consequences for group decisions too. For example, observational learning can become pathological as individuals choose to follow and imitate others' actions and choices instead of using their own information in a cascade leading to herding effects (Hirshleifer, 1995; Raafat, Chater, & Frith, 2009; Smith & Sorensen, 2000; Torney, Lorenzi, Couzin, & Levin, 2015). These effects can decrease the diversity of behaviours, increase group bias and reduce the collective accuracy (Koriat, 2012; Lorenz, Rauhut, Schweitzer, & Helbing, 2011; Lux, 1995; Muchnik, Aral, & Taylor, 2013; Stasser & Titus, 1985) sometimes with deadly consequences (Esser &

Lindoerfer, 1989; J. J. Faria, Krause, & Krause, 2010). Indeed, it is very often the case that deliberating groups are inflicted with social influence factors such as such as peer pressure and obligation to reach consensus, leading to “Madness” of the crowds (Janis, 1972; Mackay, 1841; Sunstein, 2004). It is therefore crucial to understand under what circumstances social influence enhances the wisdom of crowds, and when it leads to madness of the crowds.

A recent theoretical investigation of wisdom of the crowds (Mavrodiev, Tessone, & Schweitzer, 2012) posited that the impact of social influence on aggregated decision may depend on (among other factors) the “state of collective error” under minimal social influence. The theory predicts that if the crowd is not particularly wise under minimal influence, social influence should help. Recently the psychological and biological determinants of the state of collective error have been extensively studied (Bahrami et al., 2010, 2012a; Bang et al., 2014; Koriat, 2012; Sorkin, Hays, & West, 2001; Woolley, Chabris, Pentland, Hashmi, & Malone, 2010; Wright et al., 2012). Many of these studies have been conducted under conditions of minimal social influence ideal for wisdom of the crowds to emerge. It has been demonstrated that even with minimal influence, the state of collective error is indeed a precarious one. Groups of independent voters can be driven to failure reliably under laboratory conditions. Mahmoodi and colleagues (2015) argued that one reason for this may be that weighting others’ opinions proportional to their competence or reliability is not an easy, nor socially rewarding, operation. Instead, cooperating individuals seem to follow a heuristic dubbed equality bias: members of a dyad contributing to a joint decision operate *as if* everyone is as competent or reliable as everyone else (Mahmoodi et al., 2015). This is a sound strategy as long as dyad members’ are actually similarly reliable. However, when a large competence gap separates the individuals’, then equality bias is, by definition, misguided and proves catastrophic for the dyad. A number of other studies shown that heterogeneity of competence among group members can substantially impair the state of collective error (Bahrami et al., 2010; Bang et al., 2014).

Mahmoodi and colleagues (2015) suggested that equality bias may be robust to feedback information because it helps the dyad members cope with a number of potential difficulties by avoiding social exclusion and sharing responsibility for joint failures. For example, when one dyad's much less reliable than the other, collective success would require that the dyad ignore the opinion of the less competent member repeatedly leading to an uncomfortable social exclusion. Moreover, in such situation, occasional errors made by the dominant (albeit more reliable) dyad member are likely to cause greater regret and more severe sense of responsibility. We wondered whether these socially awkward situations could be avoided if the pre-condition of independence of voting was relaxed. Specifically, removing the independent voting stage and allowing for maximal social influence might, paradoxically one may argue, remove the explicit disagreements and allow the dyad to consistently choose the more reliable opinion without incurring the social costs such as exclusion and regret. That such positive impact of social influence on collective performance should only be observed when a wide competence gap separates the dyad members is also consistent with Mavrodiev et al (2012) who predicted that social influence should be beneficial when a substantial collective error is observed under minimal social influence.

In order to test this hypothesis, we employed a recently developed paradigm for uncertainty-ridden collective decision making (Bahrami et al., 2010) which allows assaying of collective and individual decision making. In order to empirically examine when social influence is beneficial and when it is detrimental for collective benefit, we examined collective decisions made by pairs (dyads) of individuals with and without making private decisions before negotiation of collective decision.

Methods

Participants were healthy male adults with normal or corrected-to-normal visual acuity, and provided a written informed consent before starting the experiment. Forty two participants (age 25.5 ±7.3;Mean ± STD) were recruited for Experiment 1, and thirty (age 26±7.9;Mean ± STD) for Experiment 2. Participants in both experiments were recruited using the UCL Division of Psychology and Language Sciences' database of registered volunteers. In order to avoid a possibility of task-irrelevant sex-stereotypical behaviour effecting our data (Buchan, Croson, & Solnick, 2008; McPherson, Smith-Lovin, & Cook, 2001) we avoided mixed-sex dyads and chose to test male participants only. Participants received a fixed monetary compensation for their contribution. Both experiments were approved by the local ethics committee.

Pairs of participants (dyads) made individual and collective decisions in a visual perceptual task (Bahrami et al., 2010). Both dyad members sat in the same room and performed a 2-interval forced choice (2-IFC) visual search for contrast oddball on stimuli presented on separate monitors (Figure 1A, and supplementary materials). In each trial, two visual search arrays (set size = 6; duration: 83ms) were presented in consecutive intervals separated by a 1000ms blank screen. One of the two search arrays contained a contrast oddball item, i.e. the target, whose contrast was higher than all other distractors. Distractor contrast was fixed at 0.10. Target contrast varied randomly between trials and was determined by addition of anyone of 0.01, 0.03, 0.07 or 015 to the distractor baseline. The task was to decide in which interval the target appeared. Target interval was randomised across trials.

The experimental conditions determined how the participants announced their decisions. These consisted of independent (IND) and influence (INF) conditions, administered in 2 separate blocks, counterbalanced across dyads (half of the dyads started with INF condition and half started with IND condition), each containing 128 trials (Figure 1A). In the IND condition, each participant initially made an independent, private, decision by pressing one of two available buttons on the mouse or keyboard. These privately made responses were then shared. If they did not agree, the dyad members proceeded to discuss their decisions and made a joint decision. The joint decision was declared by one of the participants using the same two buttons that they had used for their private response. Announcing the joint decision was delegated to the participant using the keyboard on odd trials and to the participant using the mouse on even trials. Feedback (‘CORRECT’ or ‘WRONG’) was given at the end of each trial for private and joint responses. In the INF condition, participants did not make any private decisions, but started the discussion immediately after stimulus offset and made a collective decision directly. Declaration of joint decisions alternated between dyad members on odd and even trials similarly to IND condition.

In experiment two, prior to the main test, each participant completed an isolated version of the same visual search task (48 trials). In this measurement, target contrast was determined dynamically using a 2-up-1-down staircase procedure(Levitt, 1971) to determine the participant's contrast sensitivity. This initial procedure allowed us to determine the more and less sensitive members of each dyad prior to starting the main experiment. In the experiment proper white noise was added to the display of this less sensitive participant, making it harder to detect the target. This procedure ensured that a substantial sensitivity gap was inserted between the two members of each dyad leading to failure of collective decision making (Bahrami et al., 2010, 2012b; Mahmoodi et al., 2015). Beside this manipulation, the IND and INF conditions followed similarly to experiment 1. The participants did not know about the selective addition of noise to one but not the other participant's stimulus and were told that the initial isolated test served as practice.

Psychometric functions were constructed for each observer (Green, Swets, & others, 1966), and for each dyad, by plotting the proportion of trials in which the oddball was reported in the second interval against the contrast difference at the oddball location (the contrast in the second interval minus the contrast in the first) (Figure 1B). The psychometric curves consisted of a cumulative Gaussian function whose parameters were bias, b, and variance, σ^2. To estimate these parameters, a probit regression model was employed using the 'glmfit' function in MATLAB (release 2013b , The MathWorks Inc., Natick, Massachusetts, United States). A participant with bias b and variance σ^2 would have a psychometric curve, denoted $P(\Delta c)$, where Δc is the contrast difference between the second and first presentations, given by

$$[1] \qquad P(\Delta c) = H\left(\frac{\Delta c + b}{\sigma}\right)$$

where $H(z)$ is the cumulative normal function,

$$[2] \qquad H(z) \equiv \int_{-\infty}^{z} \frac{dt}{\sqrt{2\pi}} e^{\frac{-t^2}{2}}$$

The psychometric curve, $P(\Delta c)$, corresponds to the probability of choosing the second interval. Thus, a positive bias indicates an increased probability of reporting the target in the 2nd interval (and thus corresponds to a negative mean for the underlying Gaussian distribution). The maximum slope of the psychometric curve, denoted s, is related to the variance via

$$[3] \qquad s = \frac{1}{\sqrt{2\pi\sigma^2}}$$

A large slope indicates small variance and thus highly sensitive performance, thus we define sensitivity as the slope. Using this measure, we quantified individual participants' as well as the dyad's sensitivity: s_{Max} for the more sensitive participant, s_{Min} for the less sensitive participant, and s_{Dyad} for the dyad sensitivity. We defined 'collective benefit' (CB) as the ratio: ${}^{s_{Dyad}}/_{s_{Max}}$. Values of collective benefit above 1 indicate that the dyad managed to gain an advantage over its better member. Values below 1 would indicate that collaboration was counterproductive and that the dyad did worse than its more sensitive member. Here we focus on slope and sensitivity of decisions. The use of a symmetric 2-IFC design ensured that overall, decision biases were negligible and did not vary systematically between the conditions.

Results

Condorcet's Jury theorem asserts that successful collective decision making would require that private opinions are elicited independently first and then aggregated. A prediction of this account that has been supported by empirical evidence is that any social influence that undermines the independence of private opinions is detrimental to the wisdom of crowds by reducing the diversity that provides the extra information earned from consulting more than one opinion (Lorenz et al., 2011). Adapting this prediction to our experiment would follow that dyadic sensitivity should be higher under IND vs INF condition. However, we did not observe any overall difference between the dyad sensitivity in the IND vs INF condition in experiment 1 (two tails paired t-test, s_{IND}= 4.6, s_{INF}=4.7, t(20) =-0.2, p = 0.86, Figure 2A). We observed considerable variability among dyads, both in dyadic sensitivity under each condition and in the direction of change in dyadic sensitivity across conditions (Figure 2A, lines in the left panel, Supplementary Figure 1A). Such variability, even under IND condition, could be indicative of different cognitive processes at work for dyads with high vs. low sensitivity under IND condition. This possibility was in line with the prediction of Mavrodiev and colleagues that increasing social influence may paradoxically benefit the dyads that failed under IND condition with minimal social influence (Mavrodiev et al., 2012). Therefore, dyads were divided into two groups: dyads that accrued collective benefit (CB>1, 12 out of 21 dyads) under IND conditions and those that failed to accrue collective benefit (CB<1, 9 dyads) (counterbalanced order of INF and IND conditions was maintained). In dyads that were successful under IND condition (CB > 1), Ten out of 12 successful dyads got worse under INF condition, and 2 dyads actually improved under INF condition (see Supplementary Figure 1A and Supplementary Dataset). Consequently, we observed a trend indicating that social influence impaired successful dyads' joint decision making (s_{IND}= 5.7, s_{INF} = 4.8, t(11) =1.5, p = 0.15, Figure 2B). Most critically for the purpose of our question, dyads who failed under IND condition (i.e. CB < 1) did significantly better with increased social influence under INF (s_{IND}= 3.2, s_{INF}=4.5, t(8) =-2.4, p = 0.04, Figure 2B)*.

The above results may be criticised as a post-hoc justification for a null result. We therefore set out to replicate this finding under experimental conditions that *ensured* collective failure in the IND condition. Recent works have underscored the importance of similarity of competence for collective

* It may be argued that the results of Experiment 1 should be qualified by an interaction in a 2 (success vs failure) x 2 (IND vs INF) ANOVA. However, the first factor (success vs failure) is not independent from the dependent measure (i.e. dyadic slope) and application of an ANOVA would be problematic. Rather than using a statistical analysis with dubious validity, we opted for seeking the more convincing evidence of replicating the surprising findings in a separate experiment.

success (Bang et al., 2014). Indeed, in Experiment 1, high performing dyads showed higher similarity in performance, measured as the ratio between the performance of the worse and best members ($^{s_{Min}}/_{s_{Max}}$) , (two tailed t-test, t(19) = 2.14, p = 0.04). Previous research showed that pairing two partners with very different abilities will be counterproductive such that the group will do worse than the better partner (Bahrami et al., 2010, 2012b; Bang et al., 2014; Mahmoodi et al., 2015). Specifically, when dyad members make joint visual perceptual decisions, adding noise to the stimuli presented to one of the dyad members (and thereby reducing similarity between individual sensitivities) drives the dyad to do worse than its own better member who did not receive noise (Bahrami et al., 2010, 2012b). In experiment 2, we used this manipulation to casually impair dyadic performance in the IND condition and predicted that these dyads should benefit from increased social influence under INF condition.

In the second experiment dyads did not accrue any collective benefit in the IND condition: as predicted, dyadic sensitivity was significantly below the sensitivity of the better member of the dyad (one tailed paired t-test, s_{IND}= 3.44, s_{Max}=3.87, t(14) =2.07, p = 0.028). Thus, our experimental manipulation succeeded in generating collective failure under minimal social influence of IND condition. Critically and replicating the results of experiment 1 even more strongly, dyadic sensitivity was significantly higher with increased social influence under INF (vs. IND) condition (s_{IND}= 3.44, s_{INF}=4.15, t(14) =2.7, p = 0.017, Figure 2C).

In order to gain a better understanding of the mechanism by which social influence might have improved collective decision making in INF condition in Experiment 2, we compared the participants' individual sensitivity under IND condition to the sensitivity of his contribution to the joint decision under IND and INF conditions separately. As noted in the Methods, on each trial, one participant, the arbitrator, announced the joint decision. Under IND condition, the arbitrator's role was restricted to disagreement trials and depending on trial number (odd or even) in the block, one of the dyad members was assigned this role. Under INF condition, because only joint decisions were made, each trial had an arbitrator, assigned by the same “odd or even trial number in block” rule. Thus, we had a complete record of who made the joint decision in each trial and were able to estimate the performance of each participant from his declared joint decisions. The participant’s decisions on behalf of the dyad could give useful insights about the role of social influence (i.e. how being able to discuss their decisions and possibly change their mind affected them). We calculated the sensitivity of the each participant’s private decisions by fitting psychometric function to their private decisions during the IND condition (Private-IND). To measure the sensitivity of a given participant’s contribution to the joint decisions, under each condition, we selected the (odd or even) trials in which the participant was designated to arbitrate for the group and calculated the slope of the psychometric function for collective choices in those trials, giving rise to joint-IND and joint-INF sensitivities (see Methods for odd and even trials). In the IND condition, these joint decisions consisted of choices made in agreement trials and in disagreement trials arbitrated by the participant. Joint decisions in agreement trials were identical to the participant’s private choices. Joint decisions in the disagreement trials arbitrated by the participant came from two sources: participant confirming his own private decision or changing his mind and adopting his partner’s choice. Consequently, if the participants tended to change their mind during disagreement, then their joint-IND sensitivity would be different from their private-IND sensitivity. In addition, a difference between the participants’ joint-IND and joint-INF would indicate a change of strategy as a consequence of increased social influence.

Given that participants’ average accuracy in private decisions was 67% ± 7% (mean ± SD) in Experiment 1 and 63% ± 8% in Experiment 2, we can calculate the expected rate of dyadic disagreement if the dyad members’ private responses were independent from one another. Like two coins flipped separately, we would expect dyad members private decisions to disagree on (0.67x0.33+0.33x0.67)*128 = 56 of the 128 trials in Experiment 1, and (0.63x0.37+0.37x0.63)*128 = 59 of the 128 trials in Experiment 2. In Experiment 1 dyad members disagreed on 49 ± 11 out of 128 trials and in Experiment 2 on 57 ± 7 out of 128 trials in the IND condition. The correspondence between the empirical and probabilistically calculated number of disagreements strongly suggests that the dyad members' private decisions in the IND condition were truly independent from one another.

By definition, and consistent with the added noise to one of the dyad members, the private-IND sensitivities of the better participants were higher than these of the worse participants. Worse participants benefited from discussion as their contribution sensitivity increased on their private sensitivity ($s_{\text{Private IND}}$ = 1.72; $s_{\text{Joint IND}}$ = 3.3; t(14) = 4.1, p = 0.001). Better participants slightly decreased their sensitivity after discussions (but not significantly so), indicating that they may over weighted the worse participants' views. During the INF condition contribution sensitivity (Joint-INF) was not different between worse and better dyad members ($s_{\text{Min joint}-\text{INF}}$ = 4.2, $s_{\text{Max joint}-\text{INF}}$ = 4. 67, t(14) = 0.7, p = 0.49; Figure 3), showing a shift in collective decisions strategy from the IND condition. The worse member of each dyad had a significantly higher joint-INF sensitivity compared to both private-IND (t(14) = 10.48, p < 0.00001) and joint- IND (t(14) = 2.46, p = 0.02), an increase that could not be attributed to changes in sensitivity, but to change in decision strategy, i.e. tendency to follow the better member's views with increased social influence in the INF condition. The better participant did not show significant difference between private-IND or joint-IND sensitivities to the joint-INF sensitivity. Similar results were observed when looking at the unsuccessful dyads in experiment 1 (see Supplementary Figure 2).

Discussion

We examined how social influence, i.e. gaining information about others' views before casting one's own vote, affects collective decisions made by pairs of participants engaged in a collective perceptual decision making task (Bahrami et al., 2010). In experiment 1, dyads with high collective benefit in the independent (i.e. minimal social influence) condition did not benefit from increased social influence; however, dyads who had failed in the independent condition did benefit from increasing the social influence. Experiment 2 replicated this surprising finding when collective failure under minimal social influence was induced by experimental manipulation. Taken together with previous works on the negative impact of social influence on wisdom of crowds, our results highlight the double edged nature of social influence, by showing that it could also enhance dyadic decisions.

Thus, social influence benefits collective decisions making when groups consist of highly heterogeneous members. Heterogeneity in performance should not be confused with independence of sampling noise. While two dyad members can have similar overall sensitivity, say detecting 75% of all the targets, under the assumption of independence of sampling noise in their private decision processes, we would expect (and observed here) that they end up correctly agreeing on (0.75x0.75=) ~56% trials. Similarly, they will agree on the wrong choice in (0.25x0.25=) ~6% of the trials. The remaining ~38% will have to be decided by negotiation. Independence of trial-by-trial sampling noise in these disagreement trials would guarantee that putting the two private choices together and following the more confident one will allow the dyad to exceed their of the better dyad member (Bahrami et al., 2010; Sorkin et al., 2001). Heterogeneity in performance, however, relates to the overall sensitivity and is evaluated over all trials. Previous research (Bahrami et al., 2012b; Bang et al., 2014) has shown that a wide gap in the overall sensitivity, seen in experiment 1 and causally inflicted in experiment2, curtails collective benefit in the IND condition. Social influence enabled the dyads to overcome this debilitating condition and improve collective decision making.

We suggest, based on previous theoretical and experimental results (Bahrami et al., 2010) that in disagreement trials, dyads comprised of similarly competent members exploit the independence of sampling noise by sharing confidence in their private decisions and achieve collective benefit. On a trial by trial basis, the member with higher confidence is more likely to be correct and joint decision based on higher confidence is more likely to be correct than a number of alternative joint decision strategies such as flipping a coin between disagreeing opinions (Bang et al., 2014). However, in a dyad with a wide competence gap, confidence information is not sufficient for efficient joint decision making because people do not weight their confidence by their differing performances (Mahmoodi et al., 2015). In other words, interacting individuals operate with an equality bias. Confidence levels that should have been weighted according to each dyad member's sensitivity are in fact taken to be equivalent, leading to underweighting of the better member's confidence and overweighting of the worse member's confidence, thereby impairing collective benefit. Mahmoodi and colleagues suggested that equality bias may be a consequence of individuals' aversion to the awkward social situations that may arise from the competence gap such as having to continuously ignore the lesser sensitive participant's opinion. Here, under IND conditions disagreements are inevitable and the only way to deal with them cordially is to employ some level of equality bias, thus sacrificing collective performance for social decorum. However, under INF condition, disagreements can be nonchalantly avoided, for example if the more sensitive participant speaks first and the less sensitive one gracefully endorses the suggested course of action. Nobody will be excluded, bored or embarrassed and noise-ridden, unreliable judgements will be successfully filtered out too. This could explain why increasing social influence helped unsuccessful dyads in Experiment 1 and Experiment 2. Support for this explanation comes from the fact that the dyad members' respective contribution to dyadic did not differ in the INF condition, which indicated that the more sensitive member dominated the joint decisions in the INF condition. In addition, such erroneous weighting of the other member's opinion (i.e. underweighting of the more sensitive member and overweighting of the less sensitive one) could explain the lack of collective benefit in the IND condition.

Our quantitative design was optimized for assessing collective benefit, relating individual and dyadic performance, by using well established analytical and experimental tools from signal detection theory. In order to achieve these advantages, this approach inevitably strays from estimation and general knowledge tasks classically used in wisdom of the crowd studies. In these studies participants estimate an unknown continuous variable such as the weight of an ox (Galton, 1907) or the population of Switzerland (Lorenz et al., 2011). Our uncertainty ridden model for collective decisions employs dichotomous decisions in a visual contrast discrimination task. At first glance, this task may not appear less ecologically intuitive than some previous works, but it conjures up a common situation in which two judges who hold different private information (due to variability in perceptual accuracy or gap in background knowledge) have to integrate their disagreeing private views and reach a collective decision. Importantly, the generalizability of this laboratory model's predictions and results has been extended to other, higher level cognitive tasks such as visual enumeration (Bahrami, Didino, Frith, Butterworth, & Rees, 2013), to object recognition (Brennan & Enns, 2014), as well as to knowledge based dichotomous questions (Koriat, 2012). We therefore suggest that individual variations in perceptual accuracy in our task (Bahrami et al., 2012b; Baird, Smallwood, Fishman, Mrazek, & Schooler, 2013; Fleming, Weil, Nagy, Dolan, & Rees, 2010) play a role similar to variations in background knowledge in estimation tasks. Similarly, the introduction of noise to one participant's display in experiment 2 is analogous to pairing experts and naïve participants in a knowledge based estimation task (Griffin & Tversky, 1992).

Extrapolating from dyadic interaction to larger groups and crowds is not trivial. A theoretical work by Migdal et al. (Migdał, Raczaszek-Leonardi, Denkiewicz, & Plewczynski, 2012) expanded the laboratory model used here to larger groups. They demonstrate that the same principles working for dyads can lead to wisdom of the crowds, as group performance increase non-linearly with group size, and depend on the gap in individual performances of group members. Furthermore, they examine different information aggregation rules, showing that in large groups, a voting system performs as well as confidence sharing by discussion (which was used under IND condition) to resolve disagreements. Lorenz et al. (Lorenz, Rauhut, & Kittel, 2015) further demonstrated in knowledge based tasks a majority vote after deliberation is worse than the median of independent votes and from unanimous decision after deliberation. Generalization from dyadic to large groups may prove to be more complex as other factors come into action in larger groups. For example, Sorkin et al. (Sorkin et al., 2001) showed that as group size increases group efficiency decreases. Larger groups performed better than small groups, but failed to fulfil their performance potential, maybe due to phenomena such as free riders, which can lead to apathy in crowds (Torney et al., 2015).

Importantly, our results that the effect of social influence is context dependent and not monolithically good or evil may also be generalized to larger groups as suggested by theoretical and experimental assessment of social influence effect on wisdom of the crowds (Mavrodiev et al., 2012; Sasaki, Granovskiy, Mann, Sumpter, & Pratt, 2013). Computer simulations of groups of voters (including pairs) estimating some unknown continuous variable suggested that the impact of social influence on wisdom of the crowds may depends on what the authors called the “starting state of collective error” under minimal social influence i.e. when the voters were not exposed to others' opinions (Mavrodiev et al., 2012). This notion was echoed in another study comparing colonies and individual ants decisions (Sasaki et al., 2013). Colonies outperformed individuals when the discrimination task was difficult, but failed when the discrimination was easy. Based on the above findings, it is conceivable that the same mechanism that enhances group decisions under high uncertainty may leads to failure when individual accuracy increases. Our results suggest that a cognitive (rather than a purely statistical) mechanism may also contribute to this effect (in humans, at least). When group members vary in their performance level, then discussion without committing to prior private opinions allows overcoming equality bias, and enhances group decisions.

Our results and the diverse impacts of social influence on groups pose the question: how can one decide a priori on the optimal collective decision strategy? We suggest that when a big gap in competence or expertise is expected, for example when a committee includes a mixture of expert and non-expert members, it is better to skip the private decision stage and proceed directly to open voting and discussion. On the other hand, groups of experts such as physicians discussing a patient can have similar knowledge but different opinions. Such homogenous group can benefit from the aggregation of private decisions. To summarise, our results suggest that deciding between one and two-stage views aggregation procedures should be done according to group characteristics.

We found that two-stage collective decisions tend to reflect the prior beliefs and biases of the decision maker (i.e. equality bias). When these beliefs reflect the reality (i.e. dyad members are truly similar in competence) two-stage procedures are beneficial for collective decisions. Single-stage joint decisions, which tend to reflect and reinforce the judgment of the better member, are more beneficial when these beliefs are misguided, i.e. in the presence of big competence gap.

Funding

This work was supported by the European Research Council Starting Grant NeuroCoDec 309865.

References

Abrahamson, E. (1991). Managerial Fads and Fashions: The Diffusion and Rejection of Innovations. *The Academy of Management Review*, *16*(3), pp. 586–612. Retrieved from http://www.jstor.org/stable/258919

Bahrami, B., Didino, D., Frith, C., Butterworth, B., & Rees, G. (2013). Collective enumeration. *Journal of Experimental Psychology. Human Perception and Performance*, *39*(2), 338–47. doi:10.1037/a0029717

Bahrami, B., Olsen, K., Bang, D., Roepstorff, A., Rees, G., & Frith, C. (2012a). 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), 3–8. doi:10.1037/a0025708

Bahrami, B., Olsen, K., Bang, D., Roepstorff, A., Rees, G., & Frith, C. (2012b). What failure in collective decision-making tells us about metacognition. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *367*(1594), 1350–65. doi:10.1098/rstb.2011.0420

Bahrami, B., Olsen, K., Latham, P. E., Roepstorff, A., Rees, G., & Frith, C. D. (2010). Optimally interacting minds. *Science (New York, N.Y.)*, *329*(5995), 1081–5. doi:10.1126/science.1185718

Baird, B., Smallwood, J., Fishman, D. J. F., Mrazek, M. D., & Schooler, J. W. (2013). Unnoticed intrusions: Dissociations of meta-consciousness in thought suppression. *Consciousness and Cognition*, *22*(3), 1003–1012. doi:10.1016/j.concog.2013.06.009

Bandura, A. (1977). *Social learning theory*. New York: General Learning Press.

Bang, D., Fusaroli, R., Tylén, K., Olsen, K., Latham, P. E., Lau, J. Y. F., … Bahrami, B. (2014). Does interaction matter? Testing whether a confidence heuristic can replace interaction in collective decision-making. *Consciousness and Cognition*, *26C*, 13–23. doi:10.1016/j.concog.2014.02.002

Bates, J. M., & Granger, C. W. J. (1969). The Combination of Forecasts. *OR*, *20*(4), 451. doi:10.2307/3008764

Bazazi, S., Ioannou, C. C., Simpson, S. J., Sword, G. a, Torney, C. J., Lorch, P. D., & Couzin, I. D. (2010). The social context of cannibalism in migratory bands of the Mormon cricket. *PloS One*, *5*(12), e15118. doi:10.1371/journal.pone.0015118

Berdahl, A., Torney, C. J., Ioannou, C. C., Faria, J. J., & Couzin, I. D. (2013). Emergent sensing of complex environments by mobile animal groups. *Science (New York, N.Y.)*, *339*(6119), 574–6. doi:10.1126/science.1225883

Blinder, A., & Morgan, J. (2000). *Are Two Heads Better Than One?: An Experimental Analysis of Group vs. Individual Decisionmaking*. Cambridge, MA. doi:10.3386/w7909

Bonabeau, E., Dorigo, M., & Theraulaz, G. (1999). *Swarm intelligence: from natural to artificial systems*. New York, NY: Oxford university press.

Brennan, A. a., & Enns, J. T. (2014). When two heads are better than one: Interactive versus independent benefits of collaborative cognition. *Psychonomic Bulletin & Review*. doi:10.3758/s13423-014-0765-4

Buchan, N. R., Croson, R. T. a, & Solnick, S. (2008). Trust and gender: An examination of behavior and beliefs in the Investment Game. *Journal of Economic Behavior and Organization*, *68*, 466–476. doi:10.1016/j.jebo.2007.10.006

Clark, C. W., & Mangel, M. (1984). Foraging and Flocking Strategies: Information in an Uncertain Environment. *The American Naturalist*, *123*(5), 626. doi:10.1086/284228

Condorcet, J.-A.-N. de C. (1785). *Essai sur l'application de l'analyse à la probabilité des décisions rendus à la pluralité des voix*. Paris: L'imprimerie Royale. Retrieved from http://www.archive.org/details/essaisurlapplica00cond

Ehrmann, J. R., & Stinson, B. L. (1999). Joint fact-finding and the use of technical experts. In *The consensus building handbook* (pp. 375–399). Thousand Oaks (CA): Sage Publications.

Esser, J. K., & Lindoerfer, J. S. (1989). Groupthink and the space shuttle challenger accident: Toward a quantitative case analysis. *Journal of Behavioral Decision Making*, *2*(3), 167–177. doi:10.1002/bdm.3960020304

Faria, J. J., Codling, E. a., Dyer, J. R. G., Trillmich, F., & Krause, J. (2009). Navigation in human crowds; testing the many-wrongs principle. *Animal Behaviour*, *78*(3), 587–591. doi:10.1016/j.anbehav.2009.05.019

Faria, J. J., Krause, S., & Krause, J. (2010). Collective behavior in road crossing pedestrians: the role of social information. *Behavioral Ecology*, *21*(6), 1236–1242. doi:10.1093/beheco/arq141

Farrell, S. (2011). Social influence benefits the wisdom of individuals in the crowd. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(36), E625; author reply E626. doi:10.1073/pnas.1109947108

Fleming, S. M., Weil, R. S., Nagy, Z., Dolan, R. J., & Rees, G. (2010). Relating introspective accuracy to individual differences in brain structure. *Science (New York, N.Y.)*, *329*(5998), 1541–3. doi:10.1126/science.1191883

Galton, F. (1907). Vox Populi. *Nature*, *75*(1949), 450–451. doi:10.1038/075450a0

Green, D. M., Swets, J. A., & others. (1966). *Signal detection theory and psychophysics* (Vol. 1). Wiley New York.

Griffin, D., & Tversky, A. (1992). The weighing of evidence and the determinants of confidence. *Cognitive Psychology*, *24*(3), 411–435. doi:10.1016/0010-0285(92)90013-R

Hirshleifer, D. A. (1995). The Blind Leading the Blind: Social Influence, Fads and Informational Cascades. In M. Tommasi & K. Ierulli (Eds.), *The new economics of human behavior* (pp. 188–215). Cambridge: Cambridge University Press. doi:10.1017/CBO9780511599040

Janis, I. L. (1972). *Victims of groupthink: A psychological study of foreign-policy decisions and fiascoes*. Houghton Mifflin.

Karl, H. a., Susskind, L. E., & Wallace, K. H. (2007). A Dialogue, Not a Diatribe: Effective Integration of Science and Policy through Joint Fact Finding. *Environment: Science and Policy for Sustainable Development*, *49*(1), 20–34. doi:10.3200/ENVT.49.1.20-34

Kerr, N. L., & Tindale, R. S. (2011). Group-based forecasting?: A social psychological analysis. *International Journal of Forecasting*, *27*(1), 14–40. doi:10.1016/j.ijforecast.2010.02.001

Koriat, A. (2012). When are two heads better than one and why? *Science (New York, N.Y.)*, *336*(6079), 360–2. doi:10.1126/science.1216549

Levitt, H. (1971). Transformed Up-Down Methods in Psychoacoustics. *The Journal of the Acoustical Society of America*, *49*(2B), 467. doi:10.1121/1.1912375

Lorenz, J., Rauhut, H., & Kittel, B. (2015). Majoritarian democracy undermines truth-finding in deliberative committees. *Research & Politics*, *2*(2), 1–19. doi:10.1177/2053168015582287

Lorenz, J., Rauhut, H., Schweitzer, F., & Helbing, D. (2011). How social influence can undermine the wisdom of crowd effect. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(22), 9020–5. doi:10.1073/pnas.1008636108

Lux, T. (1995). Herd Behaviour, Bubbles and Crashes. *The Economic Journal*, *105*(431), 881. doi:10.2307/2235156

Mackay, C. (1841). *Memoirs of extraordinary popular delusions and the Madness of Crowds*. London: Richard Bentley.

Mahmoodi, A., Bang, D., Olsen, K., Zhao, Y. A., Shi, Z., Broberg, K., … Bahrami, B. (2015). Equality bias impairs collective decision-making across cultures. *Proceedings of the National Academy of Sciences*, *112*(12), 3835–3840. doi:10.1073/pnas.1421692112

Mavrodiev, P., Tessone, C. J., & Schweitzer, F. (2012). Effects of Social Influence on the Wisdom of Crowds. *arXiv:1204.3463v1*. Physics and Society. Retrieved from http://arxiv.org/abs/1204.3463

McPherson, M., Smith-Lovin, L., & Cook, J. M. (2001). Birds of a Feather: Homophily in Social Networks. *Annual Review of Sociology*. doi:10.1146/annurev.soc.27.1.415

Migdał, P., Raczaszek-Leonardi, J., Denkiewicz, M., & Plewczynski, D. (2012). Information-sharing and aggregation models for interacting minds. *Journal of Mathematical Psychology*, *56*, 417–426. doi:10.1016/j.jmp.2013.01.002

Muchnik, L., Aral, S., & Taylor, S. J. (2013). Social influence bias: a randomized experiment. *Science (New York, N.Y.)*, *341*(6146), 647–51. doi:10.1126/science.1240466

Raafat, R. M., Chater, N., & Frith, C. (2009). Herding in humans. *Trends in Cognitive Sciences*, *13*(10), 420–8. doi:10.1016/j.tics.2009.08.002

Sasaki, T., Granovskiy, B., Mann, R. P., Sumpter, D. J. T., & Pratt, S. C. (2013). Ant colonies outperform individuals when a sensory discrimination task is difficult but not when it is easy. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(34), 13769–73. doi:10.1073/pnas.1304917110

Smith, L., & Sorensen, P. (2000). Pathological Outcomes of Observational Learning. *Econometrica*, *68*(2), 371–398. doi:10.1111/1468-0262.00113

Soll, J. B., & Larrick, R. P. (2009). Strategies for revising judgment: how (and how well) people use others' opinions. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *35*(3), 780–805. doi:10.1037/a0015145

Sorkin, R. D., Hays, C. J., & West, R. (2001). Signal-detection analysis of group decision making. *Psychological Review*. doi:10.1037/0033-295X.108.1.183

Stasser, G., & Titus, W. (1985). Pooling of unshared information in group decision making: Biased information sampling during discussion. *Journal of Personality and Social Psychology*, *48*(6), 1467–1478. doi:10.1037//0022-3514.48.6.1467

Sunstein, C. R. (2004). Group Judgments: Deliberation, Statistical Means, and Information Markets. *SSRN Electronic Journal*, *80*, 962–1049. doi:10.2139/ssrn.578301

Surowiecki, J. (2005). *The wisdom of crowds*. *Economies, Societies and Nations*. Random House LLC.

Torney, C. J., Lorenzi, T., Couzin, I. D., & Levin, S. a. (2015). Social information use and the evolution of unresponsiveness in collective systems. *Journal of the Royal Society, Interface / the Royal Society*, *12*(103). doi:10.1098/rsif.2014.0893

Woolley, A. W., Chabris, C. F., Pentland, A., Hashmi, N., & Malone, T. W. (2010). Evidence for a collective intelligence factor in the performance of human groups. *Science (New York, N.Y.)*, *330*(6004), 686–8. doi:10.1126/science.1193147

Wright, N. D., Bahrami, B., Johnson, E., Di Malta, G., Rees, G., Frith, C. D., & Dolan, R. J. (2012). Testosterone disrupts human collaboration by increasing egocentric choices. *Proceedings. Biological Sciences / The Royal Society*, *279*(1736), 2275–80. doi:10.1098/rspb.2011.2523

Yaniv, I. (2004). Receiving other people's advice: Influence and benefit. *Organizational Behavior and Human Decision Processes*, *93*(1), 1–13. doi:10.1016/j.obhdp.2003.08.002

Zarnowitz, V. (1984). The accuracy of individual and group forecasts from business outlook surveys. *Journal of Forecasting*, *3*(1), 11–26. doi:10.1002/for.3980030103

Figure Captions

Figure 1 – Experimental Design

(A) In experiment 1 pairs of male participants (Dyads) performed two experimental conditions together – independent (IND) and influence (INF). Conditions were counterbalanced across dyads. Experiment 2 was identical to experiment 1, but initiated with a staircase procedure carried for each participant individually. This procedure was used to determine the less sensitive participant, and noise was added to his stimuli in the experiment proper. Each trial started with two stimulus intervals. Visual stimuli consisted of six vertically oriented Gabor patches that were displayed equidistantly around an imaginary circle. One (randomly selected) interval contained the target of higher contrast. In the IND condition participants indicated their individual decisions privately. If they disagreed a joint decision was negotiated and announced. Feedback about accuracy was provided. In the INF condition participants did not make an individual decision but immediately negotiated joint decision. Feedback on joint decision was provided at the end of each trial. (B) Psychometric functions from one dyad relating group choice to stimulus strength in Experiment 1. The proportion of trials on which the observer reported that the target was presented in the second interval is plotted as a function of the target's contrast difference from on targets. The data is than fitted with cumulative psychometric function, resulting with estimate of bias in the responses and slope of the curve reflecting sensitivity of target detection. Steeper estimated slope indicates highly sensitive performance, i.e. accurately identifying the target even in hard trials when the contrast is very low. (C) Participants sat in the same testing room, each viewing his own display. Display screens were placed on separate tables at a right angle to each other. A thick cardboard screen was used to occlude the half not viewed by the participant in experiment 2. Both participants used their right hand to respond.

Figure 2 – Collective Performance

The sensitivity of dyads in the odd ball task was estimated by the slope of the psychometric function fitted to dyadic decisions.(A) Overall mean dyadic sensitivity wasn't significantly different between the INF and IND conditions of experiment 1. The effect of social influence was highly variable between dyads (each lines depict one dyad), as were the dyadic sensitivities. (B) Dyads in experiment 1 were separated according to their collective benefit (CB) observed in the IND condition. The sensitivity of successful dyads (CB>1) slightly decreased under INF condition but sensitivity of unsuccessful dyads (CB>1) increased under social influence (* $p < 0.05$). (C) In experiment 2 we added noise to the display of one dyad member, causally lowering dyadic performance. The surprising result from experiment 1 was replicated, as social influence significantly increased dyadic sensitivity in the INF condition (** $p < 0.02$). All Error bars represent 1 SEM.

Figure 3 – Individual Performance and Contribution in Experiment 2

We examined individual performance level in experiment 2. First we fitted the psychometric function to the private choices made by participants in the IND condition to obtain private decisions sensitivities (private-IND). We then used half of the trials (odd/even) to obtain participants' contribution sensitivities in the IND condition (Joint-IND) and in the INF condition (Joint-INF). Odd/even trials in the IND condition included half of the agreement trials and the disagreement trials arbitrated by the participant. Joint -IND sensitivity and private-IND sensitivity diverge when the participant changed his mind during disagreements. Odd/even trials in the INF condition (Joint-INF) include all the joint decisions arbitrated by the participant. We present these sensitivities for better dyad members and worse dyad members separately. (A) In experiment 2 the less accurate member benefitted from discussions after making private decisions (joint-IND > private-IND) but the better members did not gain a similar benefit, and got slightly worse. The absence of private initial decisions in the INF condition allowed better members to dominate the dyadic decisions declared by themselves as well as those declared by their inferior partner. This can be seen in the increase in performance of the worse member (joint-IND vs joint-INF) (* $p < 0.05$, ** $p < 0.005$, *** $p < 0.00005$). All Error bars represent 1 SEM. (B) Better dyad member's sensitivities are plotted against the worse member's sensitivities. Dyad members have big gap in private performance (left panel) and become more similar after discussion in the IND condition, as worse members get better and better members get slightly worse. In the INF condition both members perform as the better members.

Figures

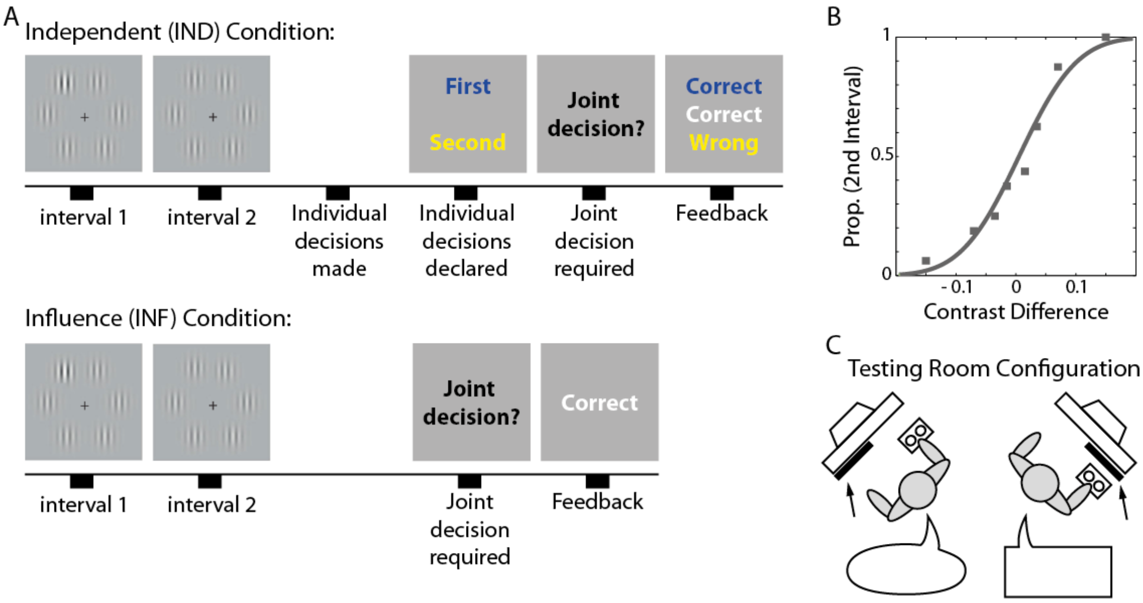

Figure 1 – Experimental Design

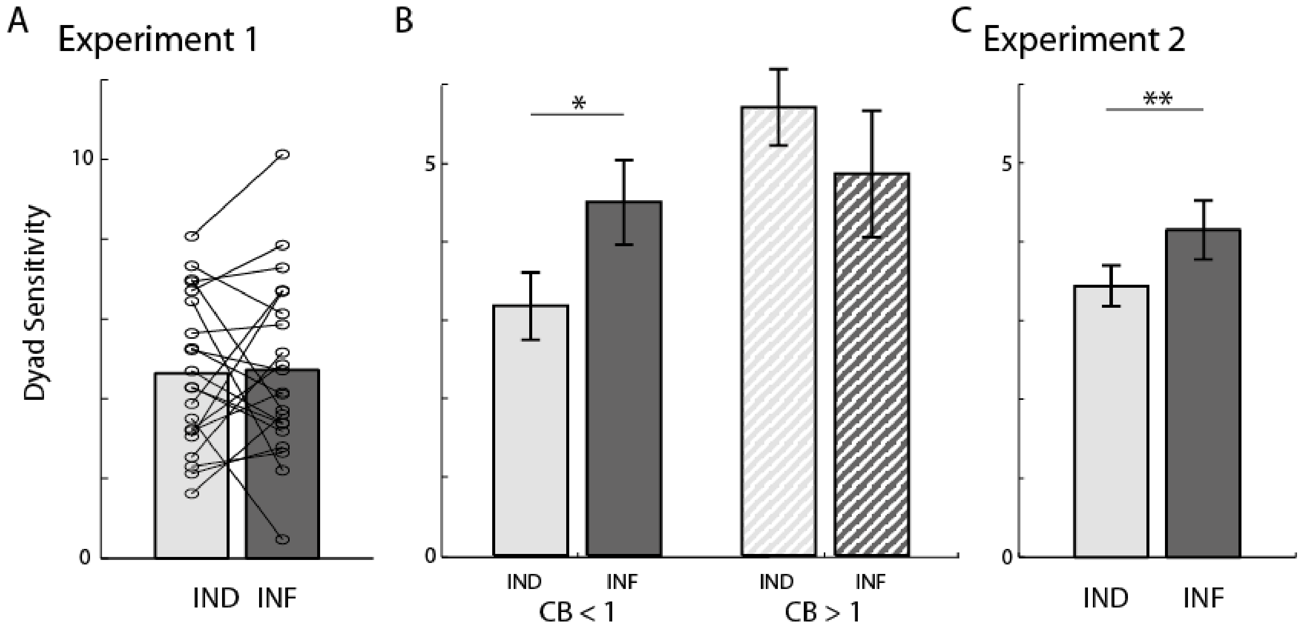

Figure 2 – Collective Performance

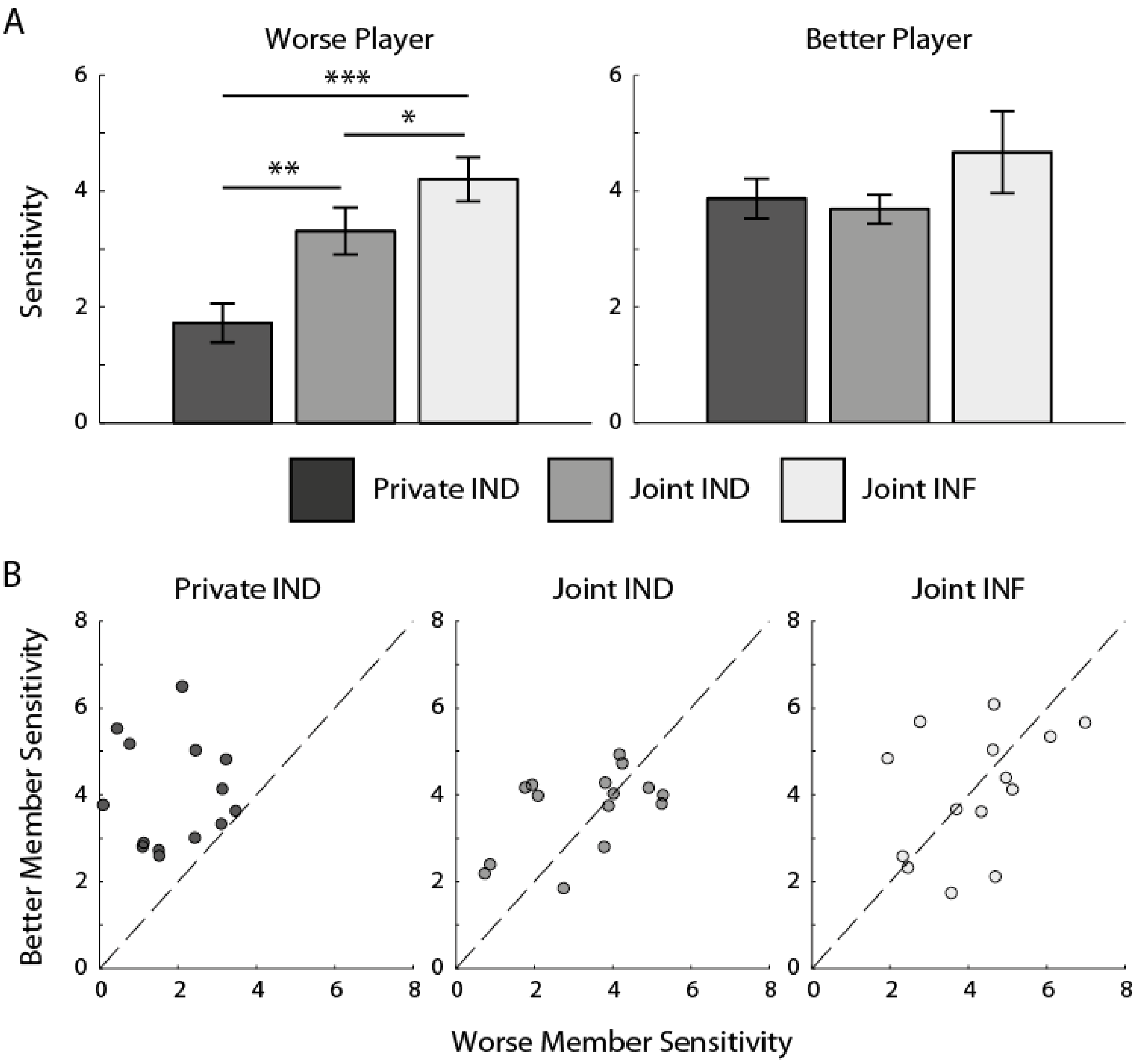

Figure 3 – Individual Performance and Contribution in Experiment 2