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## Theoretical proofs of evolutionary stabilities in indirect reciprocity of private assessment

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Private assessment in indirect reciprocity is a natural assumption because individuals can assess others privately in this situation. However, only few studies have considered private assessment because of analytical difficulty that it presents. Here, we develop an analytical method using solitary observation to solve private assessment in indirect reciprocity problem without any approximation. In this study, we formulate a model of solitary observation and calculate the replicator dynamics systems of five leading norms of indirect reciprocity. Our theoretical solution shows that indirect reciprocity in private assessment provides a different result to that in public assessment.

According to the existence proofs of cooperative evolutionarily stable (CES) points in the system, strict norms (stern judging and shunning) have no CES point in private assessment, while they do in public assessment. Image scoring does not change the system regardless of the assessment types because it does not use second-order information. In tolerant norms (simple standing and staying), the CES points move to co-existence of norms and unconditional cooperators. Surprisingly, although there is no central coercive assessment system in private assessment, the average cooperation rate is greater than that in public assessment. This is because private assessment gives unconditional cooperators a role because the unconditional cooperators can raise the cooperation level of the society.

Our results also show the three advantages of the staying norm in private assessment: a higher cooperation rate, easiness of invasion into defectors, and robustness to maintain cooperative evolutionarily stable situations. Our results are applicable to general social dilemmas in relation to private information. Under some dilemmas, norms or assessment rules should be carefully chosen to enable cooperation to evolve.

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