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ORIGINAL PAPER

Quantum Cooperation

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Abstract In a theoretical simulation the cooperation of two insects is investigated who share a large number of maximally entangled EPR-pairs to correlate their probabilistic actions. Specifically, two distant butterflies must find each other. Each butterfly moves in a chaotic form of short flights, guided only by the weak scent emanating from the other butterfly. The flight directions result from classical random choices. Each such decision of an individual is followed by a read-out of an internal quantum measurement on a spin, the result of which decides whether the individual shall do a short flight or wait. These assumptions reflect the scarce environmental information and the small brains' limited computational capacity. The quantum model is contrasted to two other cases: In the classical case the coherence between the spin pairs gets lost and the two butterflies act independently. In the super classical case the two butterflies read off their decisions of whether to fly or to wait from the same internal list so that they always take the same decision as if they were super correlated. The numerical simulation reveals that the quantum entangled butterflies find each other with a much shorter total flight path than in both classical models.

Keywords Quantum entanglement · Insects · Biological systems · Thermal creation of quantum entanglement · Numerical simulation of insect behavior

1 Introduction

Quantum games (Klimovitch 2004; Brassard et al. 2004) have been a much discussed topic ever since experiments on Bell's inequality proved the non local correlation of statistical measurements made by remote observers. The existence of

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such correlations has also given rise to speculations that they might exist naturally in biological systems (Josephson and Pallikari-Viras 1991; Hagan et al. 2002).

In recent model calculations, which were motivated by the surprising coincidences between the decisions of individuals found in everyday life, it was surmised that such coincidences might be due to quantum correlations. It was shown that, if it actually does exist, quantum entanglement between the apparently random decisions of individuals could unobtrusively guide their actions to achieve a common goal more efficiently than otherwise possible (Summhammer 2005). One of the examples in that work was about two butterflies who are far apart and who want to find each other. A similar problem was posed in Brukner et al. (2006). The two butterflies can only receive few scent molecules from the other one to allow an approximate orientation where to fly. But the butterflies are chaotic beings whose flight directions vary and are of a random stop-and-go fashion. Nevertheless, it turned out that if the random actions of the one butterfly are quantum entangled with the random actions of the other one, the total flight paths until they find each other are reduced by as much as 50% compared to non-entangled butterflies.

In this paper I will extend this example and compare the possible achievements of the quantum entangled butterflies not only to those of independent ones, where the actions of the two individuals are completely uncorrelated, but also to those of super classically correlated butterflies. The purpose of the latter is to see whether a relatively simple, but very strong classical correlation, could lead to even better achievements than quantum correlations. It will be shown that this is not the case.

In the analysis of why the quantum entangled butterflies have to fly a shorter distance until they find each other, particular emphasis will be placed on the fact that *quantum decisions* always give uncontrollable random results, such that an individual cannot willfully force a decision and hope that another individual will make a similar quantum entangled decision. If this were possible, it would mean actual transfer of information, and this is something which quantum entanglement cannot do. Furthermore, I will underline how very hypothetical the example really is in view of the thermal environment of living systems. The thermal field drives decoherence and destroys almost immediately the relatively simple form of quantum correlations of our example. However, I will also point to complex forms of entanglement, which cannot only persist for longer periods of time, but which are continually recreated by the thermal radiation. If such permanent creation of entanglement between distant quantum systems could be proven experimentally, it might have significance for living organisms.

2 Two Butterflies Looking for Each Other

With certain kinds of butterflies it is known that a male and a female can find each other even when they are initially many kilometers apart. The classical explanation is that each butterfly emanates scent molecules to guide the other one. The huge antennas of a butterfly capture the molecules, permitting it to determine the gradient of the distribution and hence the direction of the origin of the scent. Nevertheless, one may wonder, whether for large distances the classical information contained in the few scent molecules is sufficient to give a butterfly a clear direction where to fly.

In the present scenario we shall assume that this classical information will allow a butterfly only to come up with a probability distribution for the directions in which it should fly. The actual choice of a flight direction is then made according to this classical probability distribution. Furthermore, we assume that the two butterflies share a large number of maximally entangled pairs of spin-$\frac{1}{2}$ particles, of which each butterfly holds one particle. The entangled state will be the singlet state, which has the form

$$|+-\rangle - |-+\rangle. \tag{1}$$

This state ensures that the two butterflies get the same measurement result, if they measure the spins along *opposite* directions. This will later increase the chance that they fly towards each other without knowing it.

The details of the scenario are as follows:

(i) The intensity of the scent emanated by each butterfly drops off as $1/r^2$ where r is the distance from the butterfly.
(ii) The propagation of the scent is very much faster than the speed with which the butterflies fly, so that each butterfly can notice a change of the distance of the other one more or less immediately as a change of intensity of the scent.
(iii) Each butterfly moves in a sequence of short straight flights of constant length. Before such a short flight the butterfly has to make two decisions in exactly this order:

- Choose a direction for the short flight.
- Decide whether to really do the short flight, or whether to have a little rest.

The first decision is resolved classically. The butterfly chooses the direction for the short flight randomly, but weighted with the probability distribution of directions which it considers appropriate in view of its experience of change of intensity of the scent in the previous short flights. In the model calculations, each butterfly can choose among 16 directions evenly spaced over 2π. In the beginning, this probability distribution is isotropic. After each short flight, the distribution is updated according to a rule explained below. The second decision comes from a quantum mechanical measurement. The butterfly takes the spin-$\frac{1}{2}$ particle designated for this short flight, and projects it along the chosen direction. If the result is "+", it does the short flight, otherwise it rests until the next short flight is due. The rule for updating the probability distribution of flight directions now looks as follows. (It is only applied, if the short flight has actually taken place. If, instead, the butterfly has taken a rest, it will retain the probability distribution from before the rest.) The butterfly measures the intensity of the scent of the other one:

- If the increase of the intensity, i.e. the average gradient of the scent along the short flight path, is above a certain threshold, the butterfly judges this to have been a good direction and enhances the corresponding probability weight by the factor $(1 + l)$. This direction is then more likely to be chosen again in one of the next short flights. The parameter l can be set between 0 and 1. When it is 0, no learning from experience occurs.

- If the increase of the intensity is below the threshold, the butterfly flies back, because it judges this to have been a bad direction. In addition, it reduces the probability weight of this direction by the factor $(1 + l)^{-1}$. This direction is then less likely to be chosen again in one of the next short flights.

The threshold is taken as a certain fraction of the strongest increase of the intensity of the scent encountered in the short flights until then. Therefore, as the butterflies get closer to each other, the threshold will get higher and they will become more discriminating in judging a short flight as having been good or bad.

This quantum scenario will now be compared to two classical scenarios. They differ from the quantum scenario only in the way the decisions before each short flight, whether to fly or to rest, are correlated between the two butterflies. The two scenarios shall be called the *independent classical* scenario and the *super classical* scenario.

2.1 Independent Classical Scenario

Here, each butterfly will decide randomly with a constant probability of 0.5 whether to fly or to rest. In other words, the choice of direction has no influence whatsoever on this second decision. This implies that the two butterflies are completely independent, and the decision of whether to fly or to rest before a short flight of one butterfly is in no way correlated with the corresponding decision of the other butterfly. From the point of view of quantum correlated butterflies this is equivalent to loss of coherence between the spin pairs.

2.2 Super Classical Scenario

This scenario is the complete opposite. Here, the decisions of the two butterflies of whether to rest or to fly after having chosen the directions of a short flight, are always the same. The choice is completely random, so that in 50% of the cases they will fly and in 50% of the cases they will rest, but they will always do the same. This can be achieved, when the butterflies measure their spins always along the same direction, and not each one along the direction it has just chosen for the next short flight. (As a common direction we might imagine the direction of the earth's magnetic field.) But the same effect can easily be obtained, if we imaginenthe butterflies to carry identical copies of a list from which each one can read off whether to fly or to rest for every decision before a short flight. The entries in that list shall be completely random. Then they will also always take the same decision of whether to fly or to rest. Therefore it seems proper to call this scenario super classical.

Figure 1 shows the screenshot of the simulation program (The Visual Basic programs QuantAnt and QuantButt can be downloaded from http://www.ati.ac.at/~summweb). The top picture (a) demonstrates actual tracks. The interesting

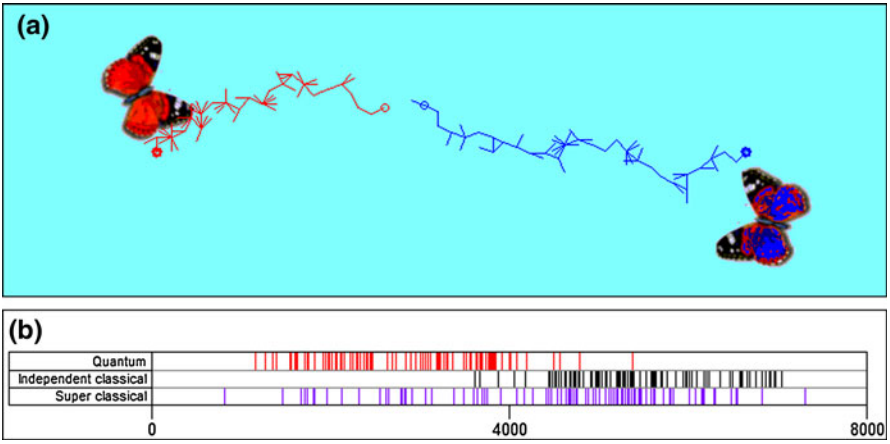

Fig. 1 **a** Typical flight paths of the two butterflies. Initial distance: 1,600. Length of one short flight: 40. Learning factor $l = 0.5$. The lines jutting out from the two main lines are short flights after which the respective butterfly had to fly back. Note that sometimes several attempts had to be made to find a good direction. **b** Statistical results of 300 quantum, 300 independent classical, and 300 supercorrelated classical runs, respectively. Initial distance: 1,600. Length of one short flight: 5. Learning factor $l = 0.5$. The quantum entangled butterflies needed an average of 2,879 short flights to find each other. The independent classical butterflies needed an average of 5,291 short flights. The supercorrelated classical butterflies needed an average of 4,322 short flights

result is the total number of short flights including the back flights, i.e., the total flight distance the two butterflies had to cover to meet. This is shown in the lower picture (b) which indicates the statistical results of 300 runs each for the quantum entangled, the independent classical, and the supercorrelated classical butterflies, respectively. The pointers in the top line indicate the number of short flights of quantum entangled butterflies, the pointers in the middle line those of the independent classical butterflies, and the pointers in the bottom line those of the super classical butterflies. It is noticeable that the quantum entangled butterflies can find each other with much fewer short flights than in both classical scenarios. This is because they decide more often simultaneously to actually do the short flight, if the chosen directions happen to point roughly towards one another. This in turn, gives more often valid short flights, i.e. short flights where the increase of the scent is above the threshold so that neither of them will have to fly back. Also, it leads to a quicker adaptation of the probability distribution of flight directions to favour the current good directions. One also notes that the super classical but also the classical butterflies sometimes need a shorter flight path than the average flight path of the quantum entangled butterflies. This is due to the statistical nature of the decisions. Especially for the superclassical scenario the range of flight paths needed until the butterflies find each other is very wide. But the average is still quite a bit above the average for the quantum entangled butterflies.

Figure 2 shows for 300 quantum, for 300 independent classical, and for 300 super classical runs, respectively, the averages and standard deviations of the total flights needed until the butterflies meet, as a function of the learning factor l. The

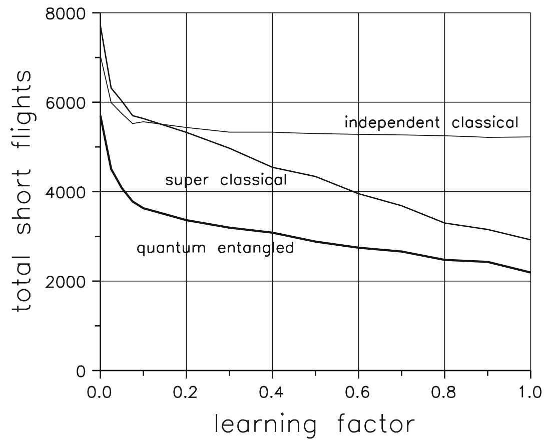

Fig. 2 Total number of short flights needed by the two butterflies to find each other, as a function of learning factor *l*. Calculated from 300 runs at each *l*, for each of the three scenarios

initial distance of the butterflies is 1,600. The length of one short flight is 5. The threshold for flying back is that the butterfly does not undo a short flight if the increase of the intensity of the scent of the other butterfly was at least 60% of the strongest increase of the scent found until then. Obviously, the quantum entangled butterflies find each other the fastest, independent of the learning factor *l*. The super classical butterflies take the longest for small learning factors, but overtake the classical butterflies in their performance when more learning from previous good directions is permitted.

It may be surprising that the quantum entangled butterflies have an advantage over the classical butterflies even for $l = 0$, i.e., when the butterflies don't learn from experience so that for all short flights all directions remain equally likely. This can be understood qualitatively when looking at the probabilities that a butterfly does *not* have to fly back after a short flight. Suppose that for the next short flight the butterflies happen to choose directions pointing exactly at each other. If both happen to really do the short flight, neither will have to fly back, because the increase of the intensity of the mutual scents will be the highest possible. Now, the probability that both will fly is $\frac{1}{2}$ for the quantum case, but only $\frac{1}{4}$ for the classical case. Classically, there is also a chance of $\frac{1}{2}$ that only one butterfly will fly, but in these cases the increase of the intensity of the scent will likely not be high enough and the butterfly will fly back. Altogether, there should thus exist an advantage for the quantum entangled butterflies. And they should have a similar advantage over quite a range of roughly forward pointing directions, the exact angular width of this range depending on the choice of threshold for flying back.

It is also interesting that the super classical butterflies need such long flight paths for small values of the learning factor. The reason seems to be the following: Since they always fly or wait simultaneously, but choose with almost equal likelihood any direction for small values of the learning factor *l*, they will need many tries until they happen to have chosen directions pointing towards each other, so that after the short flight the mutual scents have become stronger and neither of them has to fly back. In principle, this argument also appliea to the independent classical butterflies, but here they don't always fly simultaneously, so that when one has done a short flight while the other has waited and the mutual scent has become weaker, at least only one of them has to fly back.

3 Further Discussion

3.1 Communication

The mutual scent of the butterflies is an important permanent communication between the butterflies. Without this information the butterflies would have no preference for flying towards each other. Even in the quantum case, where for any spin pair the spin carried by butterfly A is always opposite to the respective spin carried by butterfly B, a measurement on a spin can give no clue to the butterfly, because it tells the butterfly nothing about the direction in which to fly, nor anything about the choice of direction of the other butterfly. For instance, the quantum correlation of the spins will give the two butterflies the same instructions of flying or resting, for directions pointing towards each other as well as for directions pointing away from each other.

3.2 Strength of Quantum Correlations

In the quantum scenario we have only looked at maximally quantum entangled decisions of the two cooperating butterflies on the one hand, and in the classical scenario we have assumed completely independent decisions on the other. Clearly, there is also the possibility of correlations whose strength lies anywhere between, e.g., purely classical correlations which would fulfill Bell's inequality. Such correlations would lead to achievements between those of the two extremes. The superclassic scenario may be seen as such. But it is clear that, with varying degrees of coherence in the quantum scenario a performance of the butterflies anywhere between the fully quantum entangled and the classical independent case can result. And if quantum entanglement does exist between individuals it is very likely that it will work at such an intermediate level, where it will not necessarily violate Bell's inequality.

3.3 Critique of the Models

The assumptions in our numerical simulations are certainly much too simple and much too technical to be found in real butterflies. It is unlikely that living systems store qubits as spin-$\frac{1}{2}$ particles and that each of these spins is entangled with a similar spin in another living system. It is even more unlikely that in successive decisions an individual resorts to just that spin which is entangled with the spin which the other individual happens to resort to for just the appropriate decision. Such clock-like synchronicity could perhaps be implemented in artificial devices, but would not appear in animals. Also, there is no reason why entanglement should exist between just two, instead of three or more individuals. Nevertheless, our simulations underline that quantum correlations between decisions of cooperating individuals—no matter how these correlations are physically realized—can enhance the cooperative achievements significantly beyond those obtainable with even the fullest exploitation of the available classical information as might be facilitated by neural networks. This is because quantum correlations do contain extra information *which is inaccessible to any individual alone* but comes to the fore with joint tasks (Toner and Bacon 2003; Svozil 2004).

The extra information in the quantum correlations is however not something which one individual communicates to the other one, not even unknowingly. The result of the measurement of the spin by one butterfly is not communicated to the other one. There is no testable influence of one on the other. All that happens is that, if the choice of directions is similar, with high probability they will get the same result of their spin measurement, independent of which butterfly does the first measurement and which one the second, or whether the measurements are done simultaneously. And then each one just behaves according to what the result of the spin measurement tells it to do: fly or don't fly. The extra information, for which the term 'information' is perhaps not appropriate, becomes manifest only in hindsight as well chosen short flights which bring the two butterflies a step closer to each other, or as 'wisely' chosen common period of rest, which at least does not increase the distance between them.

3.4 How is Entanglement Possible?

Having made the above criticisms we mention a few results, which might lend support to entanglement within or between living systems, because they address the two important issues of creation and persistence of entanglement. The references are only an entry to the literature.

Let us first look at the creation of entanglement. Entanglement arises automatically from interactions with several possible outcomes (Zhang et al. 2003). This mode is virtually excluded in our scenarios, because we assumed that the two mutually entangled parts in the butterflies are protected. The relevant mechanism must therefore work through intermediaries. This has been much studied in the context of quantum computation. One such possibility is entanglement swapping (Pan et al. 1998). It requires auxiliary systems which are already entangled, and which then interact with the systems to be entangled. The process can be repeated arbitrarily, but the final entanglement gets more and more diluted. Another possibility is that the systems to be entangled each interact in succession with one external system. This has been done with two atoms passing a cavity one after the other (Phoenix and Barnett 1993), and with two macroscopic Cs-samples, which one after the other were traversed by a beam of light (Julsgaard et al. 2001). A related possibility is that the third system interacts independently with the two systems to be entangled, and is then subjected to frequent measurements later on (Wu et al. 2004). Here one can also have more intermediate systems. This is a favourable mechanism, because the systems which lie between the two entangled parts in the two insects will be measured permanently by the thermal environment.

Now to the issue of persistence, which means the slow-down of decoherence. That decoherence need not set in immediately has been estimated in a different context for the microtubuli of the brain where quantum states can exist for relatively long periods (Hagan et al. 2002; Hameroff and Penrose 1996). Recently, it has been found for certain kinds of entangled states that the entanglement of M subsystems, each consisting of many spin-$\frac{1}{2}$ particles, becomes more robust against destructive interactions with the environment, when the number of particles per subsystem increases (Bandyopadhyay and Lidar 2004). The most robust entanglement is obtained when there are only $M = 2$ subsystems. (The experiment showing entanglement between two macroscopic samples of Cs-atoms seems to confirm this (Julsgaard et al. 2001)). For our models this could mean that entanglement between just two living systems is more likely than between three or more systems, and that the entangled systems should have many degrees of freedom, which is certainly the case for bio-molecules. The findings of Zukowski et al. (Kaszlikowski et al. 2000) and of Mermin (1990) point in the same direction. Both works show that the violation of Bell inequalities, and thus the strength of correlations, becomes stronger with higher dimensional systems. A further result, which shows that quantum states need not decohere immediately in a thermal environment, comes from the study of the state of a central spin coupled to a spin bath (Tessieri and Wilkie 2003; Dawson et al. 2004): If there is strong entanglement *within* the spin bath, the initially pure state of the central spin will decohere into a mixed state only slowly.

Even if the questions of creation and protection of entanglement are solved, there is still the problem that in our models sequential and synchronized projections of the entangled spins were needed. For entanglement to work in living systems, one would probably need very massive entanglement, such that it is possible for one animal to blindly probe any tiny fraction of its part of the entangled system and for the other animal to do the same on any other tiny fraction, and yet a strong correlation of the results should obtain. It is conceivable that, due to global conservation of angular momentum, specific configurations of many spins exhibit such properties. But details remain to be worked out.

4 Conclusion

We have modeled the chain of *sensing, deciding and acting* in the cooperation of two butterflies in three different scenarios. One was quantum entanglement between the two insects, another one was complete independence, and the third one introduced a kind of rigid classical correlation. We have seen that the quantum mechanical correlation of the statistical decisions of the two individuals is clearly an advantage. The two butterflies can find each other with much shorter total distances which they have to fly. This is favorable in terms of energy use, but also reduces the evolutionary pressure to develop complex classical means of communication and thus increases the chance of survival. Nevertheless, it must be realized that actual processes in nature will involve many more parameters than our models. The value of the models is rather instructive because they show that, in moments of hesitation and indecision, an "inner voice" in the form of the result of a quantum measurement can be of great help to an individual in achieving a goal of common interest to the species. Therefore, there may have been an evolutionary path which relies on quantum entanglement for certain decisions individuals need to make despite insufficient information. It may have been simpler for nature to exploit quantum correlations, which come about quite accidentally all the time, rather than to invent elaborate schemes of improved classical communication.

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