Bandyopadhyay, Paterek, and Kaszlikowski reply:

Paterek, Tomasz; Kaszlikowski, Dagomir; Bandyopadhyay, Jayendra N.

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Bandyopadhyay, Paterek, and Kaszlikowski Reply: In their Comment [1,2] Gauger and Benjamin question the conclusion of our recent Letter [3] that taking into account additional behavioral experiments on migratory birds shortens the required lifetime of the radical pairs (RPs), and the coherence time of their spins, to about a few microseconds. They argue that (i) there is an error in our numerical code and (ii) we do not take into account experimental data showing that birds disorient at 15 nT radio frequency (rf) field [4].

Concerning our numerics, we used the Crank-Nicholson algorithm to calculate the evolution of the RP system. We checked the code and indeed found the missing numerical factor that translates into the scaling of four as described in the Comment. Therefore, all our lifetime estimations should be multiplied by four.

With the corrected code, we also run again the calculations for the sensitivity of the compass in the presence of environmental noise. It turns out that long lifetimes do not allow for increase of the sensitivity due to noise. This effect is only seen for short lifetimes of about a microsecond (see also Supplemental Material to Refs. [3] and Refs. [5,6]).

Concerning point (ii), we had the following reservation about experimental data for the rf field of 15 nT: numerics and intuition indicate that the disruption should increase with the strength of the rf field. Experimental results of 480 nT (Fig. 2 of Ref. [4]) and 48 nT and 5 nT (Fig. 3 of Ref. [4]) are consistent with this intuition; although the average direction of flight is undefined, more birds fly in the right direction when field strength is decreased (this is also the case for the results in the static field of 92 μ T). Only for the 15 nT rf field and static geomagnetic field there are no birds flying in the right direction. The results for the rf field of 15 nT in the presence of the static field of 92 μ T look more robust but show a small directional preference. Due to this reservation, we did calculations up to rf field strength 47 nT and would like to note that this is already only 1% of the geomagnetic field strength. The lifetime estimation for 92 μ T static field and 15 nT rf field is about 180 μ s. Here we assume that the 30% functional window also exists about this stronger static field [3].

We conclude with some general remarks. Our research program was to use the data from available behavioral experiments in order to verify if the radical pair model allows a parameter regime that is consistent with all of them and with other laboratory experiments, such as those on cryptochrome [7]. The cryptochrome remains to date the only candidate for the RP magnetoreceptor, and the lifetime of RP was reported to be only a few microseconds.

We find it unlikely that the pairs would live longer in the environment of a bird's eye. Although the new microscopic criteria for the disruption of the compass we proposed in Ref. [3], in general, allows longer lifetimes than those observed, for particular strengths of radio frequency field, the lifetimes are shorter than those presented in Ref. [8], indicating their usefulness. Other methods were used to estimate the lifetime of the order of a few microseconds [4,9].

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- [1] E. M. Gauger and S. C. Benjamin, preceding comment, *Phys. Rev. Lett.* **110**, 178901 (2013).
- [2] Online Document, <http://dx.doi.org/10.6084/m9.figshare.660856>.
- [3] J. N. Bandyopadhyay, T. Paterek, and D. Kaszlikowski, *Phys. Rev. Lett.* **109**, 110502 (2012).
- [4] T. Ritz, R. Wiltschko, P. J. Hore, C. T. Rodgers, K. Stapput, P. Thalau, C. R. Timmel, and W. Wiltschko, *Biophys. J.* **96**, 3451 (2009).
- [5] J. Cai, F. Caruso, and M. B. Plenio, *Phys. Rev. A* **85**, 040304(R) (2012).
- [6] M. Tiersch and H. J. Briegel, *Phil. Trans. R. Soc. A* **370**, 4517 (2012).
- [7] T. Biskup, E. Schleicher, A. Okafuji, G. Link, K. Hitomi, E. D. Getzoff, and S. Weber, *Angew. Chem., Int. Ed. Engl.* **48**, 404 (2009).
- [8] E. M. Gauger, E. Rieper, J. J. L. Morton, S. C. Benjamin, and V. Vedral, *Phys. Rev. Lett.* **106**, 040503 (2011).
- [9] J. A. Pauls, Y. Zhang, G. P. Berman, and S. Kais, [arXiv:1211.4255v1](https://arxiv.org/abs/1211.4255v1).