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 μT). 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 μT 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 μT static field and 15 nT rf field is about 180 μs. 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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Comment on "Quantum Coherence and Sensitivity of Avian Magnetoreception"

Several papers [1–3] have studied the quantum physics of the radical pair mechanism hypothesized to underlie the avian compass. Our 2011 Letter [2] analyzed the coherence time of the electron spin pair and found that it must be surprisingly long. To be consistent with behavioral studies on European Robins involving weak radio frequency (rf) fields [4,5], the coherence time should be of order 100 μs or more. Interestingly, this is considerably longer than the reported 6 μs radical pair lifetime from *in vitro* experiments on cryptochrome [6], widely considered a potential candidate for the avian compass [7].

Utilizing the radical pair model we described in Ref. [2], Bandyopadhyay *et al.* seek to close this gap by considering additional behavioral studies, as reported in a very recent Letter [8]. However, their analysis suffers from two errors: an erroneous numerical computation together with the omission of vital experimental data. These issues are multiplicative and result in an underestimate of the lower bound by a factor of about 40. Consequently, the estimate of the lifetime given in the paper as 5–6.7 μs, and described as "of the order of a microsecond" in their abstract, in fact becomes 200–270 μs, i.e., hundreds of microseconds.

To test the validity of Bandyopadhyay-Paterek-Kaszlikowski's (BPK) numerical calculation, we regenerated their simulation results using exactly the model and the parameters which they select. After an exhaustive series of simulations, we conclude that it is not possible to reproduce the graphs in BPK's Letter. One can match the line shapes exactly, but to do so one must rescale by a factor of four either the time axis or the spins' g-factors. In an online document [9], we provide complete details of our analysis for scrutiny. Furthermore, we have been made aware that an independent researcher also found it impossible to reproduce BPK's results without artificially scaling the model parameters [10]. Evidently, there is an error in the numerical code employed by BPK.

In deriving lifetime estimates, both our original Letter and BKP's vitally depend on the effect of weak resonant fields in disrupting the birds' compass sense. Experimentalists have reported disruptions for fields of strength 470 nT to 15 nT. In our paper we took the value of 150 nT to ensure a conservative estimate; however, to argue that a specific shorter process timescale is consistent with the body of behavioral experiments, the analysis should be based on the weakest rf field known to disrupt the bird's compass sense, i.e., 15 nT. BPK perform their calculations for $B_{\mathrm{rf}} = 470$, 150, and 47 nT, but inexplicably they omit the crucial 15 nT datum (see Fig. 3 of Ref. [5], which BPK cite as their Ref. [13]). The effect of including this result is to increase the lower bound on the lifetime by a factor of about 10, which becomes 40 in view of the numerical error described above [9]. Stated alternatively: the timescale reported by BKP is not consistent with the reported disruption of the avian compass at fields of 15 nT; any bird whose compass lifetime is confined to microseconds (or indeed 10s of microseconds) must be immune to a 15 nT oscillatory field.

BKP's observation that long coherence is not required for a compass sense remains correct. However, this is not a novel observation, having been stated and analyzed in our 2011 Letter [2] and in Ref. [3]; the latter specifically examined the cases where noise is beneficial. Notwithstanding the puzzle of why the bird should evolve an unnecessarily long lifetime [11], the available data [4,5,12] applied to a proper quantum mechanical model of the radical pair mechanism nevertheless indeed imply that the life- and coherence time is of order 100 μs or more.

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