2. Rihtman, B., Puxty, R.J., Hapeshi, A., Lee, Y.-J., Zhan, Y., Michniewski, S., Waterfield, N.R., Chen, F., Weigele, P., Millard, A.D., *et al*. (2021). A new family of globally distributed lytic roseophages with unusual deoxythymidine to deoxyuridine substitution. Curr. Biol. *31*, 3199–3206.

3. Stern, A., and Sorek, R. (2011). The phage-host arms-race: Shaping the evolution of microbes. Bioessays *33*, 43–51.

4. Samson, J.E., Magadán, A.H., Sabri, M., and Moineau, S. (2013). Revenge of the phages: defeating bacterial defences. Nat. Rev. Microbiol. *11*, 675–687.

5. Takahashi, I., and Marmur, J. (1963). Replacement of thymidylic acid by deoxyuridylic acid in the deoxyribonucleic acid of a transducing phage for *Bacillus subtilis*. Nature *197*, 794–795.

6. Kirnos, M.D., Khudyakov, I.Y., Alexandrushkina, N.I., and Vanyushin, B.F. (1977). 2-aminoadenine is an adenine substituting for a base in S-2L cyanophage DNA. Nature *270*, 369–370.

7. Sleiman, D., Garcia, P.S., Lagune, M., Loc'h, J., Haouz, A., Taib, N., Röthlisberger, P., Gribaldo, S., Marlière, P., and Kaminski, P.A. (2021). A third purine biosynthetic pathway encoded by aminoadenine-based viral DNA genomes. Science *372*, 516–520.

8. Zhou, Y., Xu, X., Wei, Y., Cheng, Y., Guo, Y., Khudyakov, I., Liu, F., He, P., Song, Z., Li, Z., *et al*. (2021). A widespread pathway for substitution of adenine by diaminopurine in phage genomes. Science *372*, 512–516.

9. Pezo, V., Jaziri, F., Bourguignon, P.-Y., Louis, D., Jacobs-Sera, D., Rozenski, J., Pochet, S., Herdewijn, P., Hatfull, G.F., Kaminski, P.-A., and Marliere, P. (2021). Noncanonical DNA polymerization by aminoadenine-based siphoviruses. Science *372*, 520–524.

10. Czernecki, D., Legrand, P., Tekpinar, M., Rosario, S., Kaminski, P.-A., and Delarue, M. (2021). How cyanophage S-2L rejects adenine and incorporates 2-aminoadenine to saturate hydrogen bonding in its DNA. Nat. Commun. *12*, 2420.

11. Gilbert, W. (1986). Origin of life: The RNA world. Nature *319*, 618.

12. Forterre, P. (2002). The origin of DNA genomes and DNA replication proteins. Curr. Opin. Microbiol. *5*, 525–532.

13. Krokan, H.E., and Bjørås, M. (2013). Base excision repair. Cold Spring Harb. Perspect. Biol. *5*, a012583.

14. Wang, Z., and Mosbaugh, D.W. (1989). Uracil-DNA glycosylase inhibitor gene of bacteriophage PBS2 encodes a binding protein specific for uracil-DNA glycosylase. J. Biol. Chem. *264*, 1163–1171.

15. Collias, D., and Beisel, C.L. (2021). CRISPR technologies and the search for the PAM-free nuclease. Nat. Commun. *12*, 555.

16. Doron, S., Melamed, S., Ofir, G., Leavitt, A., Lopatina, A., Keren, M., Amitai, G., and Sorek, R. (2018). Systematic discovery of new antiphage defense systems in the microbial pan-genome. Science *359*, eaar4120.

17. Millman, A., Bernheim, A., Stokar-Avihail, A., Fedorenko, T., Voichek, M., Leavitt, A., Oppenheimer-Shaanan, Y., and Sorek, R. (2020). Bacterial retrons function in anti-phage defense. Cell *10*, 1551–1561.

18. Bernheim, A., Millman, A., Ofir, G., Meitav, G., Avraham, C., Shomar, H., Rosenberg, M.M., Tal, N., Melamed, S., Amitai, G., and Sorek, R. (2021). Prokaryotic viperins produce diverse antiviral molecules. Nature *589*, 120–124.

19. Poole, A., Penny, D., and Sjöberg, B.-U. (2001). Confounded cytosine! Tinkering and the evolution of DNA. Nat. Rev. Mol. Cell. Biol. *2*, 147–151.

20. Hoshika, S., Leal, N.A., Kim, M.-J., Kim, M.-S., Karalkar, N.B., Kim, H.-J., Bates, A.M., Watkins Jr., N.E., SantaLucia, H.A., Meyer, A.J., *et al*. (2019). Hachimoji DNA and RNA: A genetic system with eight building blocks. Science *363*, 884–887.

Neurobiology: The power of pauses in electrocommunication

Federico Pedraja and Nathaniel B. Sawtell*
Department of Neuroscience, Zuckerman Mind Brain Behavior Institute, Columbia University, New York, NY 10027, USA
*Correspondence: ns2635@columbia.edu
https://doi.org/10.1016/j.cub.2021.06.028

A new study of social communication behavior in weakly electric fish identifies neural mechanisms that may account for the significance of silent pauses in communication.

The pause — that impressive silence, that eloquent silence, that geometrically progressive silence which often achieves a desired effect where no combination of words, howsoever felicitous, could accomplish it[1].

Intentional pauses are a common feature of communication behavior. Pauses in human speech serve numerous functions, including marking syntactic or phonological boundaries, providing time for the speaker to plan or to take a breath, and signaling to the receiver that it is her turn to speak[2]. As Twain noted, strategically placing pauses before or after important words or phrases can also be a powerful device for conveying or amplifying a speaker's message. Although the communicative functions of pauses have been studied in a variety of species from grasshoppers to frogs to nightingales[3–5], little is known about the neural mechanisms that explain the power of a well-timed pause.

In this issue of *Current Biology*, Kohashi and colleagues[6] address this question using behavioral and electrophysiological studies of electrocommunication behavior in weakly electric fish. Weakly electric fish possess electric organs that generate electrical fields, known as electric organ discharges (EODs)[7]. Some species emit continuous quasi-sinusoidal EODs while others emit brief EOD pulses (on the order of 1 ms in duration) separated by much longer inter-pulse intervals (IPIs) ranging from 10–500 ms (Figure 1). Weakly electric fish also possess

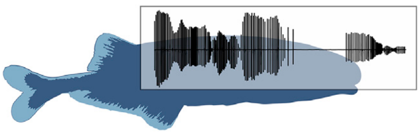

Figure 1. Communication in electric fish.
A recording of EOD pulses emitted by a pair of weakly electric fish of the species *B. brachyistius* (blue silhouette). A distinct pause is evident in the latter half of the recording.

electroreceptors distributed over their skin that allow them to sense their own EODs as well as those of other fish. These remarkable specializations allow weakly electric fish to detect objects based solely on their electrical properties (a sense known as active electrolocation) and provide them with a private channel for social communication.

Kohashi *et al.*[6] studied a pulse-type electric fish species belonging to a large African clade known as the Mormyrids. It is well known from past studies that mormyrids vary their IPIs during social encounters, including courtship[8], territorial aggression[9], and group hunting[10]. However, whereas past studies of electrocommunication in mormyrids have focused mainly on burst-like IPI patterns, Kohashi *et al.*[6] focused on the possible social significance of pauses defined by IPIs greater than 500 ms. The authors found that pauses occurred more frequently when fish were housed in groups versus in isolation, consistent with a possible social function. Intriguingly, fish were more likely to emit an EOD burst following a pause in their own discharge. Moreover, experiments in pairs of fish showed that artificial pauses introduced into a stream of EODs produced by a sender elicited increases in the EOD rate of the receiver.

Electrocommunication in mormyrids is mediated by a dedicated neural pathway beginning with a specific sub-class of electroreceptors, known as the knollenorgans[11]. Although knollenorgans are activated by the fish's own EOD as well as by the EODs of other fish, the effects of the former are completely gated out at the first central stage of processing in the hindbrain[12]. In contrast to the ascending mammalian auditory pathways, where the processing of social versus non-social acoustic signals occurs within the same neural hardware, social communication signals in mormyrids are processed separately from those used for electrolocation. These features make the mormyrid electrocommunication system highly advantageous for revealing neuronal mechanisms for social communication.

Kohashi *et al.*[6] focused their electrophysiological recordings on the posterior exterolateral nucleus (ELp), a midbrain region homologous to the mammalian inferior colliculus that has been previously implicated in IPI processing[13]. Extracellular recordings of population activity as well as intracellular recordings from individual ELp neurons revealed that responses to trains of EOD pulses exhibited synaptic depression, i.e. response amplitude diminished over time as a result of repetitive stimulation. The time course over which response amplitude recovered was ~1 second, similar to the duration of pauses observed in behaving fish. These results suggest a simple physiological explanation for the behavioral significance of pauses: by providing relief from synaptic depression, pauses enhance neural responses in the brain of the receiver. Consistent with this hypothesis, the time course of recovery of behavioral responses to identical EOD trains was highly similar to that of neural responses in ELp.

The possibility that relief from synaptic depression underlies the communicative significance of pauses is exciting, in part, because synaptic depression is a well-documented feature of synapses in many brain regions, including in the mammalian auditory pathways and cerebral cortex. The study of Kohashi *et al.*[6] also highlights the utility of neuroethological approaches for social neuroscience. Given their tractable nervous systems, the richness of their social lives, and the ease with which electrocommunication signals can be measured and manipulated in both laboratory and field environments[14,15], important progress can be expected from continued studies of electric fish.

REFERENCES

1. Twain, M. (2019). In Autobiography of Mark Twain, Volume 3, H.E. Smith, and B. Griffin, eds. (University of California Press), p. 170.
2. Rochester, S.R. (1973). The significance of pauses in spontaneous speech. J. Psycholinguist. Res. *2*, 51–81.
3. Zelick, R.D., and Narins, P.M. (1982). Analysis of acoustically evoked call suppression behaviour in a neotropical treefrog. Anim. Behav. *30*, 728–733.
4. von Helversen, D., Balakrishnan, R., and von Helversen, O. (2004). Acoustic communication in a duetting grasshopper: receiver response variability, male strategies and signal design. Anim. Behav. *68*, 131–144.
5. Brumm, H. (2006). Signalling through acoustic windows: nightingales avoid interspecific competition by short-term adjustment of song timing. J. Comp. Physiol. A *192*, 1279–1285.
6. Kohashi, T., Lube, A.J., Yang, J.H., Roberts-Gaddipati, P.S., and Carlson, B.A. (2021). Pauses during communication release behavioral habituation through recovery from synaptic depression. Curr. Biol. *31*, 3145–3152.
7. Nelson, M.E. (2011). Electric fish. Curr. Biol. *21*, R528–R529.
8. Wong, R.Y., and Hopkins, C.D. (2007). Electrical and behavioral courtship displays in the mormyrid fish Brienomyrus brachyistius. J. Exp. Biol. *210*, 2244–2252.
9. Bell, C.C., Myers, J.P., and Russell, C.J. (1974). Electric organ discharge patterns during dominance related behavioral displays ingnathonemus petersii (mormyridae). J. Comp. Physiol. *92*, 201–228.
10. Arnegard, M.E., and Carlson, B.A. (2005). Electric organ discharge patterns during group hunting by a mormyrid fish. Proc. Biol. Sci. *272*, 1305–1314.
11. Bell, C.C., and Szabo, T. (1986). Electroreception in mormyrid fish: Central anatomy. In Electroreception, T.H. Bullock, and W. Heiligenberg, eds. (Wiley), pp. 319–322.
12. Bell, C., and Grant, K. (1989). Corollary discharge inhibition and preservation of temporal information in a sensory nucleus of mormyrid electric fish. J. Neurosci. *9*, 1029–1044.
13. Baker, C.A., and Carlson, B.A. (2014). Short-term depression, temporal summation, and onset inhibition shape interval tuning in midbrain neurons. J. Neurosci. *34*, 14272–14287.
14. Fortune, E.S., Andanar, N., Madhav, M., Jayakumar, R.P., Cowan, N.J., Bichuette, M.E., and Soares, D. (2020). Spooky interaction at a distance in cave and surface dwelling electric fishes. Front. Integr. Neurosci. *14*, 561524.
15. Henninger, J., Krahe, R., Kirschbaum, F., Grewe, J., and Benda, J. (2018). Statistics of natural communication signals observed in the wild identify important yet neglected stimulus regimes in weakly electric fish. J. Neurosci. *38*, 5456–5465.