Andrea Welsh is a PhD student in physics, **Edwin Greco** is a faculty member in the physics department, and **Flavio Fenton** is an associate professor of physics and Welsh's thesis adviser at the Georgia Institute of Technology in Atlanta.

Dynamics of a human spiral wave

Andrea J. Welsh, Edwin F. Greco, and Flavio H. Fenton

With a few simple instructions, participants at the Atlanta Science Festival mimicked a phenomenon that can have fatal consequences in biological systems.

Spiral waves, which travel along expanding circular paths, are a feature of many physical, biological, and chemical systems. Some of their most dramatic manifestations are in the human body. For example, spiral waves can occur on the tongue in migratory glossitis, a condition in which the papillae—the bumps that cover the upper part of the tongue and house the taste buds—are missing due to inflammation of the mucous membrane, and the patterns of smooth patches can propagate as spirals. They also occur in the cortex of the brain, where they can lead to epilepsy.

The most dangerous spiral waves occur in the heart (see the PHYSICS TODAY articles by Leon Glass, August 1996, page 40, and Alain Karma and Robert Gilmour, March 2007, page 51). There, spiral waves of electrical activity (see figure 1) can induce tachycardia, an anomalously high resting heart rate, as the spiral propagation drives the heart to contract more frequently. When spirals break into multiple spiral waves, the heart is in a state of fibrillation, a condition of rapid unsynchronized contraction that fails to pump oxygenated blood to the body. Without intervention, fibrillation is deadly; in the US alone, it claims some 300 000 lives annually.

In Mexican-wave behavior, individuals start in the resting state: with arms down by their sides. The threshold is triggered in a person who sees a nearest neighbor to the left or right lift their hands over their head; the individual then becomes excited by raising their own hands for a specified time. After that activation, the individual lowers their arms and is in the refractory state until their arms are all the way down.

Atlantans make waves

Mexican waves propagating through large groups of people are commonplace. We wanted to see if a spiral wave could also be formed by a large group of people, a feat that had not been reported in the literature. In the process, we hoped to teach the Atlanta, Georgia, community about the deadly effect of cardiac spiral waves.

In 2014 and 2015, we performed an experiment during the city's annual Atlanta Science Festival. In each of the two events, 500–600 people were organized into approximately square grids. All the participants were provided with the rules for forming the Mexican wave, with one crucial change: For the spiral wave, any of the four nearest neighbors can trigger individual participants to raise their hands.

Excitable crowds

Just as cells in biological systems can exhibit complex collective behavior, groups of people also can display emergent behavior at larger scales. That's what happens in mosh pits, where music fans' dancing behavior is like flocking patterns, and in sports stadiums where fans form the propagating Mexican wave, so called because it became popular internationally after being broadcast during the 1986 FIFA World Cup in Mexico. In those cases the crowd is acting like a so-called excitable medium, a group whose individual entities—or "cells," be they biological cells or human spectators—have a well-defined resting state; a threshold state that, when reached, triggers the cell to become excited for a period of time; and a refractory period, following the excitation, during which the cell cannot be excited.

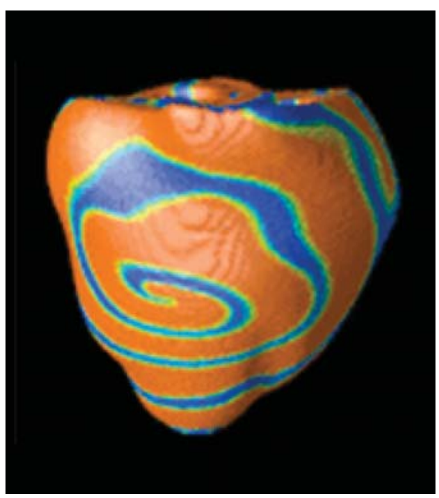

FIGURE 1. IN THE HEART, spiral waves of peak electrical activity (orange in the dramatized simulation pictured here) can lead to high heart rates or, if they break up, to fatal uncoordinated contractions.

A spiral wave could propagate in either the clockwise or counterclockwise direction, and nothing in the rules we provided determines one possibility instead of the other. To break the symmetry and realize a particular propagation direction, we had to set up specific initial conditions. As shown in figure 2a, we started with a line of excited elements extending from about the center of the crowd to the midpoint of one boundary. We required that the people to the right of the excited elements be refractory for a brief period of time, which ensured that they would not be activated by their neighbors at the start, though they could be activated later on. By changing which side of the initially excited line was made refractory, we could change the clockwise or counterclockwise chirality of the spiral wave.

Once the initial condition was set, participants were asked to follow the rules

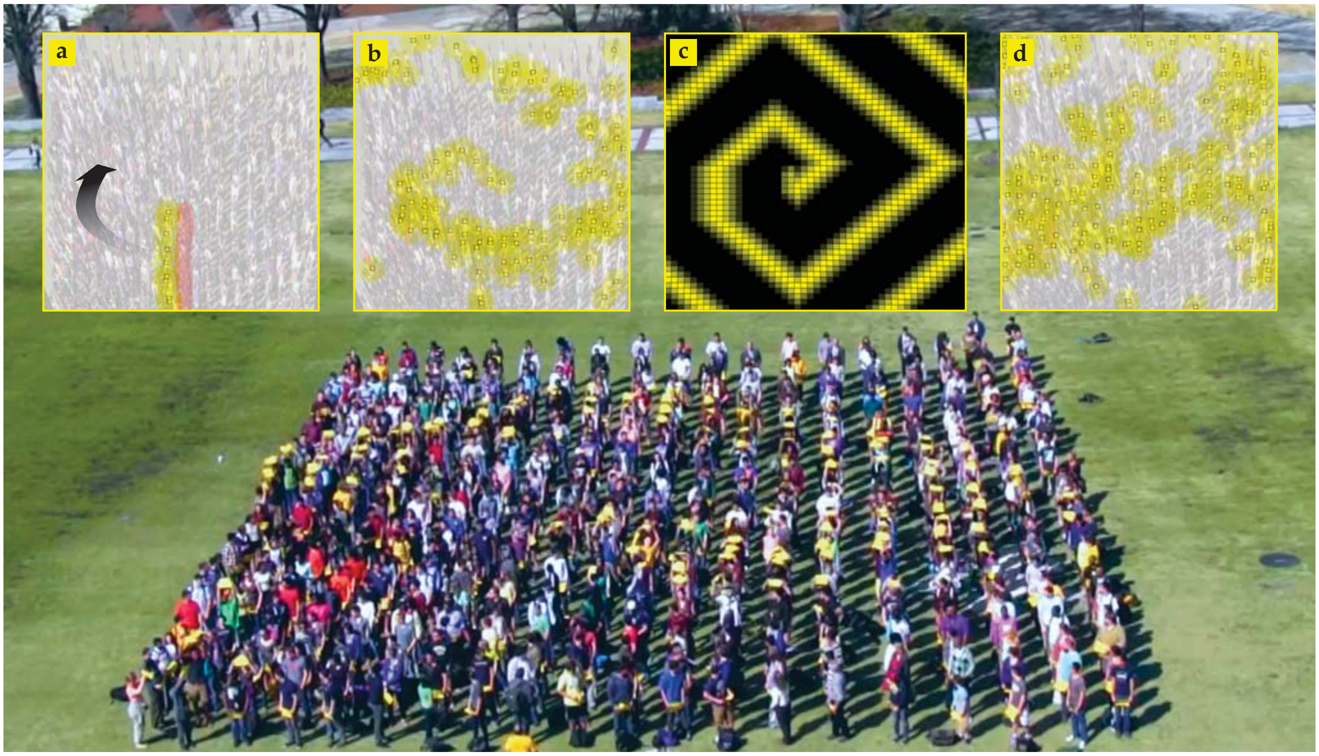

FIGURE 2. AT AN ATLANTA SCIENCE FESTIVAL outreach activity (background photo), people formed a spiral wave. **(a)** To ensure clockwise propagation of the wave, a line of volunteers (holding up square sheets and highlighted in yellow) began the exercise in the excited state with arms raised while their neighbors to the right (pink) were in the refractory state—unable to be excited for a specified period. **(b)** The people holding up sheets (yellow) display the characteristic shape of a spiral wave. **(c)** When a computer simulation rigorously follows the rules given to festival participants, the resulting wave (yellow) is much sharper. **(d)** Some human spiral waves persist, but others become disordered as indicated by the highlighted individuals with raised sheets.

we had distributed; we recorded a video of the group dynamics from the roof of a nearby seven-story building. We were not sure if the exercise would really work. It's significantly more difficult to follow four nearest neighbors than it is to observe one in the direction from which a Mexican wave is propagating. People do not react and follow rules identically, and various glitches could prevent the formation and propagation of the spiral wave. However, as shown in figure 2b and the videos available with the online version of this Quick Study, spiral waves formed quite readily. In many cases, they survived for several rotations.

Analysis of the experiments showed that the waves had a width of seven people, an average propagation speed of the wavefront of about three people per second, and a rotation period averaging 4.5 seconds.

We were able to reproduce those values in a computer simulation in which the time step was 0.25 seconds and the cells were excited for 2 seconds and refractory for 1.5 seconds. A striking difference emerged between experiments and simulations. The computer simulations produce spiral waves that follow a diamond shape, as shown in figure 2c, instead of the curved spiral waves formed in a crowd of real people. The smoothness of the human-generated waves arises because people have small differences in their reaction times and because they actually respond to more than just their four nearest neighbors.

Spatiotemporal disorder

Many systems that exhibit spiral waves eventually manifest complex spatiotemporal dynamics when the spirals break into multiple spiral waves. In our experiments with crowds, we were pleasantly surprised to sometimes observe that phenomenon (see figure 2d). Breakup of the original spiral wave was driven by small variations in reaction times between participants, who sometimes excited themselves too early and sometimes too late. In addition, a few participants excited themselves without any close neighbor being excited.

The demonstration at the Atlanta Science Festival serves as an excellent example of how aggregations of a simple element—a person armed with a few rules—can generate new, emergent behavior whose spatial and temporal dynamics is much more complex than is realized in a single exemplar. Collections of real people following the rules can form not only simple waves such as the Mexican wave but also spiral waves. They can also develop complex spatiotemporal disorder. Furthermore, our outreach exercise shows that a few single elements suffice to destabilize a spiral wave and create irregular dynamics, which underscores the ease with which small system changes can lead to fibrillation in the heart and similar if less grave behavior in other systems.

We are grateful to NSF for support of this research.

Additional resources

▶ E. M. Cherry, F. H. Fenton, "Visualization of spiral and scroll waves in simulated and experimental cardiac tissue," *New. J. Phys.* **10**, 125016 (2008).

▶ J. L. Silverberg et al., "Collective motion of humans in mosh and circle pits at heavy metal concerts," *Phys. Rev. Lett.* **110**, 228701 (2013).

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