

Applications of Circular Data

A Supplement to “*Working with Circular Data: A Tutorial for Cognitive and Behavioral Research*”

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Many areas of behavioral and cognitive research involve data that are either inherently circular or benefit from being conceptualized as circular in order to design experiments or analyze data. To illustrate its broad practical relevance, this supplemental material presents use cases of circular statistics, including for spatial, temporal, and neural data. For definitions of the used abbreviations, see Table S1.

Spatial and Directional Data

Circular statistics can be a valuable tool for behavioral research using spatial data. Many aspects of spatial cognition and behavior naturally involve circular variables, while in other cases spatial features that are not inherently circular may be constrained to a circular subspace for purposes of experiment or analysis. In the following, we will look at examples of both.

As described in the introduction, compass direction is an inherently circular spatial feature, with animal navigation and migration as a classic use case. Factors supporting navigation include the relative direction of the sun (Giraldo et al., 2018; Lindecke et al., 2019), moonlight and stars (Foster et al., 2019; Freas et al., 2024), and, in some animals, the orientation of magnetic fields (Packmor et al., 2024; Panagopoulos et al., 2024). Circular statistics have been used to study movement directions in migration routes of birds (Bolón et al., 2025; Ghosh et al., 2024; Packmor et al., 2024), insects (Huang et al., 2024; Vijayan & Somanathan, 2024), and mammals (Thompson et al., 2024). Circular statistics have also been employed to study movement patterns on smaller scales, such as bee waggle dances. This complex form of non-verbal, symbolic communication allows forager bees to inform each other about food sources: the angle of the waggle run relative to gravity encodes the angle of the food source in relation to the sun. Circular statistics allow for an appropriate analysis of these complex dances (Deverell, 2003; Schürch & Couvillon, 2013; Vijayan & Somanathan, 2024).

Location in space is an example of a feature that, although not circular by nature, may be structured circularly to support experimental design. In human vision research, for instance, it is common to record responses of experimental participants to visual stimuli presented via a computer display. If stimuli were presented at random locations across the whole display, differences in their retinal eccentricity (distance of the image from the central foveal region of the retina) would influence how they are processed by the visual system (Oliviers, 2025; Staugaard et al., 2016). Additionally, the stimuli’s varying proximity to the borders of the screen could influence how they are perceived (Fortenbaugh et al., 2012; May & Zhaoping, 2009; Schulz-Hildebrandt, 2025). Confining stimulus locations to an invisible circle on the display, while instructing participants to fix their gaze on a point at its center (see Stimulus Presentation in Figure S1A; Eriksen and Colegate, 1971), is a common experimental technique that reduces variability by ensuring all stimuli are viewed at the same eccentricity and comparable distances from the screen edges. In this design, stimulus location can be incorporated into the behavioral analysis as a circular variable, equal to its angular position on the circle (Favila et al., 2022; Schneegans & Bays, 2017).

The psychophysical method of analog reproduction on a circle, developed by Prinzmetal et al. (1998), was subsequently extended by Wilken and Ma (2004) to study visual working memory – the cognitive resource that retains and manipulates information on the order of seconds. In contrast to previous methods that made a binary measurement of whether or not an object was remembered, their cued recall task (see Figure S1) allowed for assessing how precisely visual information can be recalled, inspiring new models of working memory capacity (Bays et al., 2009; Fougner et al., 2012; Ma et al., 2014; van den Berg et al., 2012). A wide range of visual features that permit circular representations have been used in this task, including color hue (Wilken & Ma, 2004), motion direction (Ester et al., 2014), and even

shape (Salmela et al., 2012).

Temporal Data

Human and animal behavior is often structured in recurring patterns, many of which follow approximately or exactly repeating cycles. Some of these cycles have a biological basis (e.g., hormonal rhythms), while others are shaped by environmental factors or, in humans, by cultural conventions (e.g., weekly schedules). Often, biological and cultural factors jointly determine how humans experience time and its influence on behavior (Patke et al., 2020).

A key feature for classifying and distinguishing periodic systems is the length of a single cycle. The most commonly studied chronobiological rhythm is the circadian rhythm (from Latin *circa* — approximately, *dies* — day), which has a period of about 24 hours. Numerous physiological and behavioral processes in humans and other animals vary systematically across the day. Among others, circadian rhythms influence sleep-wake cycles (Saper et al., 2005; Zisapel, 2018), hormone secretion (Nelson et al., 2025; Zisapel, 2018), body temperature (Refinetti, 2020), and activity patterns (Lautenschlager et al., 2024; Palmeirim et al., 2025). In humans, the internal circadian cycle slightly exceeds 24 hours, but external cues — such as daylight and social structures — entrain it to a 24-hour rhythm. Figures S2A and S2B show a schematic of sleep-wake patterns in the presence and absence of time-of-day cues, respectively. In the former, sleep is entrained to a 24-hour rhythm with only random day-to-day variability, whereas in the latter, sleep times progressively drift to later hours in the absence of external cues.

In other periodic systems, cycle lengths vary between individuals or across repetitions, without external constraints enforcing a fixed duration. Even in such cases, circular statistics can be used after an appropriate rescaling of the data. For instance, the human menstrual cycle averages around 28 days but shows considerable inter- and intraindividual variability (Bull et al., 2019; Cunningham et al., 2024). To enable circular analysis, each cycle can be interpolated to a standardized length — typically 28 days (Alzueta et al., 2024; Gombert-Labedens et al., 2024; Sides et al., 2023). Interpolation is conducted by rescaling each cycle's data proportionally to the reference duration, allowing for meaningful comparisons across individuals and repetitions. Figure S2C shows a schematic of estrogen levels of two hypothetical cis-women across three menstrual cycles. Note that the two people display more similar patterns after the data has been normalized (Figure S2D).

Some behavioral rhythms are entirely culturally constructed. For example, the seven-day week, which structures work-rest patterns, primarily originated from religious traditions. Research employing circular statistics has indicated that the weekly cycle influences stress levels (Karoly et al., 2018; Liu & West, 2016) and even the onset of the menstrual

cycle (Ecochard et al., 2024). Certain aspects of behavior and cognition also display annual rhythms. This includes hormone levels (Tendler et al., 2021) and brain activity (Meyer et al., 2016) in humans, as well as hibernation and breeding in other animals (Kondo et al., 2006; Paul et al., 2008; Stouffer et al., 2013).

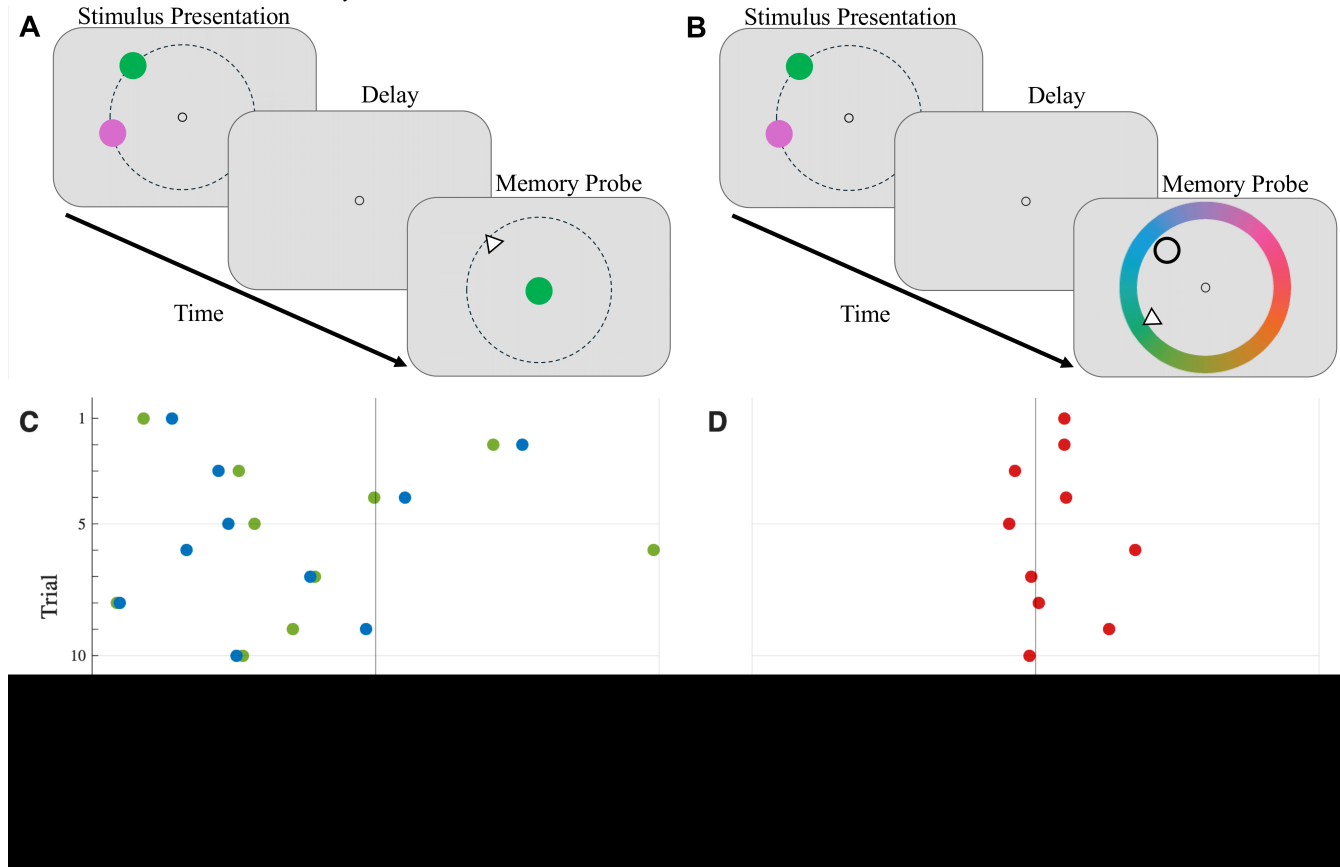
Note that temporal circular data may display autocorrelation structure (e.g., if consecutive cycles are more alike than cycles further apart in time), which violates the independence assumptions of many circular statistical tests.

Neural Data

In the previous subsections, we discussed behavioral studies involving spatial and temporal features that are intrinsically circular, or constrained experimentally to be. In the following, we examine how circular statistics have been applied to investigate neural processes related to circular features or that have periodic properties themselves.

The discovery of the columnar organization of the primary visual cortex (V1) by Hubel and Wiesel (1962) was a major advance in sensory neuroscience, recognized by a Nobel Prize. Through electrophysiological recordings in V1 in cats and monkeys, they identified neurons that were selectively responsive to specific orientations of a visible bar or grating presented on a flat screen. Each cell had a “preferred” orientation that caused it to be most active (Figure S3A), and neurons with similar orientation preferences were grouped into vertical columns (Hubel & Wiesel, 1962, 1968; Hubel et al., 1977). These orientation columns form orderly, repeating patterns across the cortical surface, often described as “pinwheels”, because preferred orientations of neurons rotate continuously around a central point, covering the full range of orientations (Blasdel & Salama, 1986; Bonhoeffer & Grinvald, 1991; Bonhoeffer et al., 1995; Maldonado et al., 1997; Ts'o et al., 1990). While Hubel and Wiesel and early follow-up studies were primarily descriptive or employed Euclidean statistics, later work recognized the circular nature of orientation data and used circular statistical methods (Blasdel, 1992; Maldonado et al., 1997; Olson & Grossberg, 1998; Ringach et al., 2002). More recent visual-processing research has applied circular statistics to investigate how many neurons are required to represent continuous spatial variables reliably (Noorman et al., 2024), to explore the neural mechanisms underlying visual illusions (Zhang et al., 2025), and to model how different visual features of an object could be jointly represented in neural activity (Schneegans & Bays, 2017).

The neural control of movement is another area where analysis of circular variables has been fruitfully employed. Georgopoulos et al. (1983, 1984) used circular statistics to study firing patterns of motor cortical neurons. They investigated the activity of neurons in the primary motor cortex (M1) of monkeys making reaching movements in the horizontal plane. They found neurons whose firing rate varied

Figure S1*Circular Data in Visual Memory Tasks*

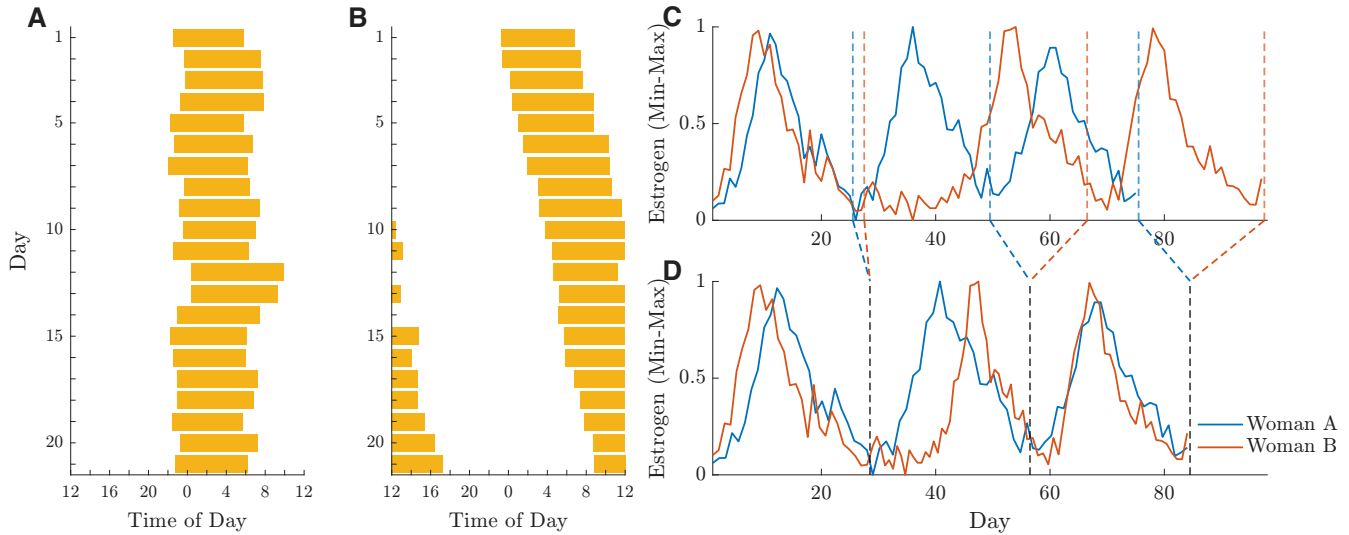
Note. (A, B) Schematic of a visual memory task where participants are presented with colored disks. After a brief delay, one stimulus is either cued by its color (green disk in the center), and participants are asked to recall its location (A), or one stimulus is cued by its location (black circle), and participants are asked to report its color by selecting the corresponding point on the color wheel (B). Note that the dashed circles are only for illustration purposes and are not presented to the participants. (C) Uniformly distributed locations of cued stimuli (green) and corresponding reports from memory of these locations (blue) by trial for the task in (A). (D) Reported locations re-centered on stimulus locations, that is, errors in memory report. All data were simulated.

as an approximately cosine function of movement direction, each with a preferred direction that induced maximum activity. By treating each neuron's instantaneous firing rate as the length of a vector pointing in its preferred direction, and summing across all neurons, they obtained a "population" vector whose direction closely matched the actual reach direction on that trial. Re-conceptualizing the motor cortex as a network that encodes higher-order features (rather than a simple map of individual muscles or body parts), Georgopoulos and colleagues laid the foundation for our current understanding of how motor cortical neurons represent abstract aspects of movement (Drew & Doucet, 1991; Georgopoulos et al., 1986; Perkins et al., 2025).

Circular statistics are also a key methodological tool in neuroscience research on spatial navigation (Moore et al., 2021; Nau et al., 2020). For instance, Seeber et al. (2025) combined

brain imaging methods and circular statistics to compare real and imagined navigation in humans. Participants first navigated real-world routes and later imagined retracing them. Neurons in the hippocampus (a brain region involved in spatial navigation) showed similar directional tuning patterns in both conditions, with different neurons responding most strongly to different movement directions, and movement directions could be reconstructed from brain activity during both real and imagined navigation.

Analysis of oscillatory neural activity ("brainwaves") is a common use case for circular statistics. A striking example of periodic neural representation of linear space is phase precession (Figure S3B–E), first observed in single-unit recordings referenced to the hippocampal theta local field potential (LFP) in rats navigating in an enclosure. In this phenomenon, certain neurons in the hippocampus (so-called place cells)

Figure S2*Human Temporal Cycles*

Note. (A,B) Schematic of a human sleep cycle with (A) and without (B) daytime cues over three weeks. Yellow bars indicate sleep periods. (C, D) Estrogen (E2) levels across three menstrual cycles of two hypothetical cis-women. (C) E2 levels aligned to the raw timeline of each individual, with cycle boundaries indicated by dashed vertical lines in the respective person's color. (D) Same data as in (C) rescaled so that each menstrual cycle spans 28 days; black dashed vertical lines mark the rescaled cycle boundaries. Note that the estrogen patterns are more similar across individuals and cycles than in (C). All hormone values were normalized to the [0, 1] range within each person (min-max scaling). Rescaling was performed cycle-by-cycle by mapping the day indices of each cycle linearly onto a standardized 28-day axis. Cycle boundaries indicate the first day of menstruation. All data were simulated.

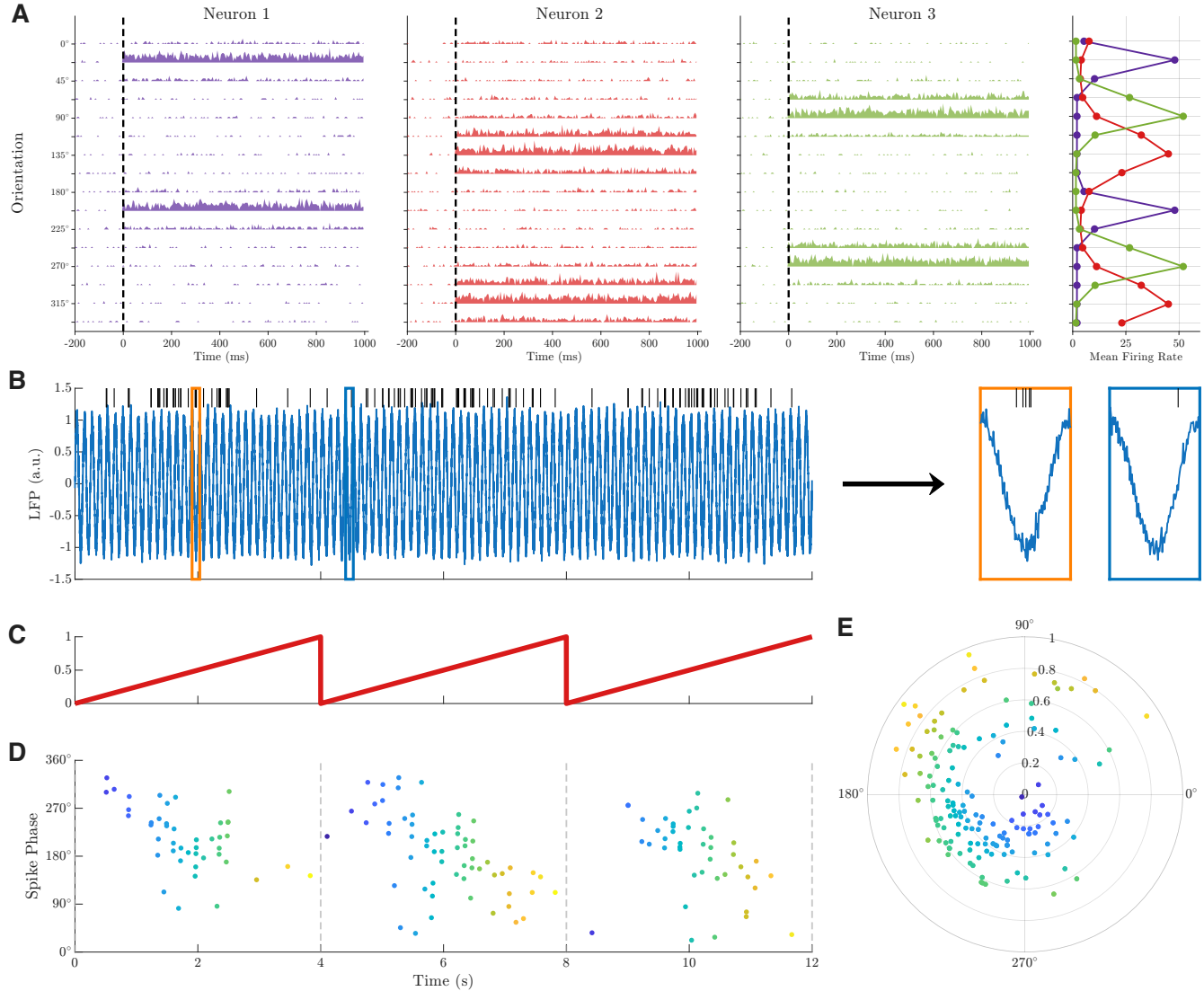
fire at times progressively earlier in the theta wave (~4–12 Hz) cycle as the rat moves through the cell's preferred location (its place field; O'Keefe & Recce, 1993; Skaggs et al., 1996). For analyzing phase-precession data, a combination of a circular representation of the periodic phase variable and a Euclidean representation of position in space has proven reliable (Kempster et al., 2012), and subsequently provided evidence for phase precession in human episodic memory (Doeller et al., 2010; Zheng et al., 2024).

Other Applications

Most examples we discussed above reflect physical measurements of time or space that have a circular or periodic structure. However, there are also more abstract perceptual, cognitive, and behavioral variables for which a circular representation is appropriate or has proven useful. For instance, circular statistics have been employed in social psychology to examine interpersonal interactions. This includes the synchronization of body movements to those of an interaction partner (Koul et al., 2023; Macpherson et al., 2024), interactions in romantic relationships (Sadikaj et al., 2015; Vowels et al., 2018), and interpersonal behavior of teachers (Cremers et al., 2021; Van Der Lans et al., 2020). The Interpersonal Circumplex (IPC) is an established model of interpersonal relationships that describes social behavior and traits along two

orthogonal dimensions: agency and communion, referring to the degree of power or control and the degree of friendliness or affiliation an individual conveys in interaction with others, respectively. Together, these two dimensions form a circular space in which interpersonal behaviors are located as angles on a circle (Gurtman, 2009; Leary, 1957; Wiggins, 1991). Figure S4A displays the IPC with anchor words describing the type of behavior located in each part of the interpersonal circle. While agency and communion are often analyzed separately, Cremers et al. (2021) argue that a circular representation integrating both dimensions more appropriately captures the angular structure of the IPC, where interpersonal behaviors are expressed as positions on a circle reflecting blends of agency and communion. The identical agency and communion scores are represented in two-dimensional Euclidean space in Figure S4B and as one circular variable in Figure S4A.

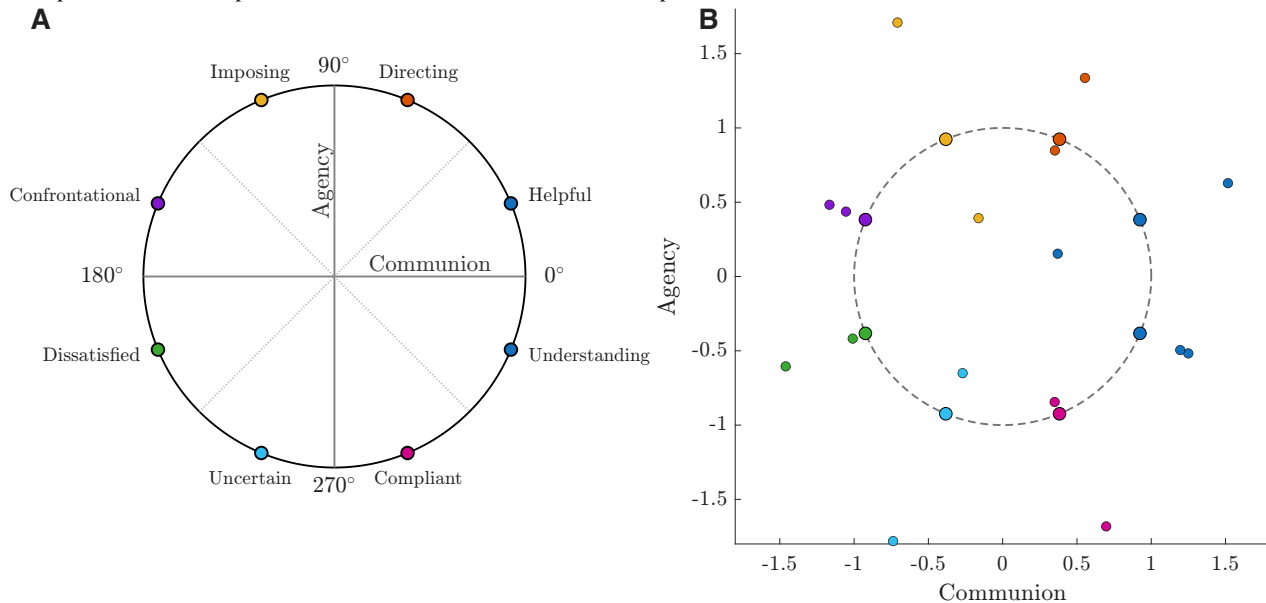
Another example is in human perception of color. Color is detected in the retina by three types of cone cells which respond preferentially to different wavelengths of light. However, in perceptual models of color, such as CIELAB (Schanda & International Commission on Illumination, 2007), different hues are arranged in a circle around a grayscale axis. Color wheels obtained as circles of constant luminance and chroma (distance from the gray axis) have been used in human psy-

Figure S3*Neural Processes with Circular Features*

Note. (A) Simulated response properties of single units recorded at the center of a pinwheel in the primary visual cortex of a hypothetical cat. The three left panels show peristimulus time histograms (PSTH) from three neurons that were stimulated by visual display of an oriented drifting square wave grating. Each row shows the PSTH for a different stimulus orientation ranging from 0° to 337.5° in 22.5° steps. Recordings are presented from 200 ms before stimulus display and 1000 ms of stimulus display, accumulated over 20 trials for each orientation. The right panel shows the mean firing rate in spikes per second for each cell and stimulus orientation. Note that the neurons vary in their orientation preferences. (B–E) Theta phase precession in place cells. (B) Simulated local field potential (LFP, 8 Hz theta rhythm) in arbitrary units (a.u.) as a hypothetical rat repeatedly traverses a spatial field. Black ticks indicate spike times from one hippocampal place cell. The two framed theta phases are enlarged on the right, illustrating how spike timings and frequencies vary for different positions in the place field. (C) Normalized position of the rat within the place field. (D) Theta phase of each spike over time. Each dot shows a single spike, color-coded by its within-field position. Note that the spike phase advances systematically within each pass. (E) Polar representation of the data in (C) with spike phases and normalized positions within the place field represented by angles and radii, respectively. Data were simulated using methods adopted from Kempter et al. (2012).

chophysical research to account for the continuous nature of perceptual and mnemonic data (Fairchild, 2013). To obtain a continuous measure of recall from visual memory, for in-

stance, participants can be asked to select the color of a previously presented stimulus from a color wheel (Figure S1B; Wilken and Ma, 2004). Operationalizing color as a circular

Figure S4*Interpersonal Circumplex Model in Circular and Euclidean Space*

Note. (A) Interpersonal Circumplex Model in circular space with anchor points (colored dots). (B) Euclidean representation of the same points as in A (large colored dots) and alternative points (small dots) that would result in the same points when constraining the data to the circle. The dashed line in (B) indicates the unit circle to which values are constrained in (A). Note that the model conceptualizes social behavior and traits continuously; the anchor points only provide orientation for interpreting values in different segments of the circle.

variable simplifies analysis, as angular error of reproduction on the color wheel can be treated as independent of the target color, whereas a linear representation in a bounded space would have to take into account the proximity of the target color to the boundary of the space.

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Appendix

List of Abbreviations

Table S1

List of Abbreviations

a.u.	arbitrary units
EEG	electroencephalography
Hz	Hertz; unit for frequency, measuring cycles per second
IPC	Interpersonal Circumplex
LFP	local field potential
M1	primary motor cortex
PSTH	peristimulus time histograms
V1	primary visual cortex