See Also: Aesthetic Response; Auditory System; Brain Specialization for Music; Music Cognition; Musical Disorders; Psychoanalysis.

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Synchronization

Synchronization generally entails the alignment of two or more events in time. Synchronization in musical contexts pervading the world's cultures takes diverse forms. Ensemble musicians synchronize the sounds that they produce and the expressive body movements that accompany their performances. Orchestral musicians synchronize with the gestures of a conductor. Dancers in pairs and larger groups synchronize their body movements with respect to one another and a musical accompaniment. People march in synchrony with music in military parades and religious processions. These examples illustrate that although synchronization is primarily a temporal process, in musical behavior it often also involves the coordination of actions in terms of spatial arrangement and intended goals, which may be aesthetic, communicative, and social in nature. Empirical research on musical synchronization has adopted multiple perspectives, drawing on theoretical concepts and investigative methods from fields within the humanities, the psychological sciences, and the biological sciences.

Cultural Influences

Research on musical synchronization in the humanities has been pursued with a mixture of ethnographic and musicological approaches. Ethnographic work has sought to understand how societal and cultural considerations affect musical synchronization. Research in this tradition uses qualitative methods, including interviews with performers and the analysis of observational data that the researcher obtains by coding events during live performances or in audio and video recordings. Systematic musicology, on the other hand, adopts quantitative approaches that entail the objective measurement of various aspects of recorded performances (sound-onset timing and body movement trajectories) in order to arrive at rich descriptions of behavior related to musical synchronization.

Studies using these approaches have revealed that systematic deviations from strict synchrony between parts played by different individuals (e.g., leader-follower relations, where one part lags behind another) are generally considered desirable in most musical genres and cultures. Such asynchronies give music vitality, rhythmic tension, aesthetic appeal, and can induce the pleasurable urge to move in listeners. "Groove"-based music, including Afro-Cuban percussion music, funk, bebop, cool jazz, and hip-hop, for instance, is characterized by intentional asynchronies of 15 to 30 milliseconds between members of the rhythm section (e.g., bass player and drummer).

The degree of asynchrony that is desirable nevertheless varies across musical traditions. For example, the tight interlocking of parts in African polyrhythm and Balinese *gamelan* is eschewed in Indian *raga*, as well as in some Western contemporary Art music and freely improvised music. Such differences are related not only to aesthetic ideals, but also to the social functions that the activity fulfills. In some religious rituals and carnival competitions (e.g., between *samba* schools), separate groups exert their identity by exhibiting tight within-group coordination while attempting to avoid coordination between groups. The ability to dynamically manipulate the degree of synchrony through a performance is also valued in some music. Analyses of jazz recordings, for instance, have revealed that soloists often lag behind the ride cymbal on downbeats but synchronize on off-beats, and that improvised performances become more synchronous immediately prior to points at which the "feel" of the music changes.

Psychological Mechanisms

Musical synchronization is underpinned by psychological processes that allow an individual to perceive the rhythm of an external sequence of events, anticipate the timing of upcoming events based on this rhythm, produce rhythmic movement, and coordinate these produced movements with events in the external sequence. There is a venerable tradition of investigating these processes in the disciplines of experimental psychology and human movement science. The bulk of research in this vein employs laboratory tasks that require an individual to synchronize simple movements (e.g., finger taps, drum strikes, or limb oscillations) with repetitive events in auditory, visual, or multimodal (e.g., audiovisual) pacing sequences.

The accuracy and precision of sensorimotor synchronization in such tasks can be quantified by measuring the phase relationship (or temporal alignment) between each movement and its corresponding pacing event, as well as the degree to which the period (or interval) of time between successive movements matches the intervals demarcated by pacing events. Accuracy is high to the extent that discrepancies in phase and period are low, while precision is high to the extent that phase and period relations are stable over time.

Factors that affect the accuracy and precision of sensorimotor synchronization include the modality of the external pacing sequence, the tempo (musical speed), and the expertise of the individual. Synchronization is typically found to be better with auditory than with visual sequences, and is possible only at tempi where the onsets between events in the pacing sequence are separated by

FuturPointe Dance performs its trademark blend of Caribbean and African dance, ballet and Latin movement, and a reggae and urban vocabulary in the Callahan Theater at Nazareth College, Rochester, New York, July 16, 2012. This type of "groove"-based music—including Afro-Cuban percussion music, funk, bebop, cool jazz, and hip-hop—is also characterized by the inclusion of intentional asynchronies, consisting of 15 to 30 milliseconds between members of the rhythm section (bass player and drummer).

100–1,800 milliseconds (600–33 beats per minute, with synchronization at fast extremes requiring biomechanical constraints on repetitive movement to be overcome by using alternating fingers, arms, or feet). Individual pacing events are difficult to perceive at faster tempi, and the timing of events is difficult to predict at slower tempi falling outside this range. Highly trained musicians are able to limit the variability of phase discrepancies to about 2 percent of the pacing interval, while variability in untrained individuals is typically at least twice as large as this.

Research in the field of sensorimotor synchronization has been steered by two main theoretical approaches. The information processing approach is concerned with the mental representation of information about event timing; the encoding, manipulation, and retrieval of such information from memory; the integration of temporal information from different sensory modalities; and the planning of movement timing.

The roots of this approach lie in psychophysical investigations of time perception dating from the late-19th century, with further fuel added by the advent of cognitivism in psychology and the birth of modern computer science in the mid-20th century. Information processing models of sensorimotor synchronization assume that neural timekeepers in an individual's brain (often conceptualized as internal clocks) trigger motor commands that control movement. It is also assumed that these timekeepers are acted upon by error correction mechanisms that serve to minimize discrepancies between movement timing and events in external sequences.

According to these models, the timing error associated with a movement is represented as an absolute duration in memory, and is then compensated for by adjusting the timing of a subsequent movement by a proportion of this represented duration. Error correction processes that adjust the phase alignment of pacing events and neural timekeepers underlying movement from one cycle to the next operate automatically (i.e., even if timing errors are subliminal), while error correction processes that alter the period of neural timekeepers are effortful, require attention, and are applied only when timing errors are large enough to be consciously perceived. Recent modeling work has supplemented reactive error correction processes with anticipatory processes that generate predictions about the timing of pacing events.

The second main approach to sensorimotor synchronization arose from the confluence of dynamical systems theory (which originated in 17th-century mechanics) and the ecological psychology movement founded by James J. Gibson in the 1960s. This approach eschews the notion of mental representations of phase and period relationships, instead favoring continuous oscillatory processes (e.g., periodic patterns of neural excitation and inhibition) that interact in such a way that synchrony naturally emerges as a form of resonance. Dynamical models use mathematical formulations, such as differential equations, to describe the temporal evolution of coupled oscillators as they undergo phase transitions between "attractor states" associated with unstable (e.g., syncopation) and stable (synchronization) coordination modes. As in the information-processing approach, it is assumed that synchronization is achieved via phase coupling and period adjustment mechanisms that serve to reduce discrepancies in the relative phase between the coupled oscillators. However, because these processes deal with relative phase relations (rather than absolute time intervals) in a mathematical space characterized by attractors that differ in strength, dynamical models are well suited to account for nonlinearities (e.g., the abrupt transitions from syncopation to synchronization that occur at fast tempi) and asymmetries (e.g., in synchronization accuracy for decelerating versus accelerating sequences).

An increasing amount of research in the information processing and dynamical systems traditions has sought to understand the psychological processes and neural mechanisms that underpin interpersonal synchrony. Work on this topic in the information-processing tradition has mainly targeted intentional coordination (such as when ensemble musicians deliberately coordinate their actions), while dynamical systems research has focused on unintentional coordination (e.g., when two individuals walking side-by-side fall into step, or when postural body sway becomes coupled between conversation partners). Thus, the distinction between these approaches can be characterized as one related to deliberately planned, versus automatically emergent coordination.

An intermediate step to studying real interpersonal synchrony has been taken by researchers who employ computer-controlled pacing signals that are programmed to respond to a human participant. The behavior of these virtual synchronization partners can be systematically manipulated in order to simulate cooperative and uncooperative interactions. Relevant musical applications include automatic accompaniment systems that track live score-based or improvised performances and generate complementary sound patterns in synchrony with the performer.

Research on real interpersonal synchrony has utilized experimental paradigms ranging from rudimentary dyadic sensorimotor synchronization tasks (e.g., pairs of individuals engaged in joint finger tapping or pendulum swinging) to naturalistic tasks such as musical ensemble performance (e.g., in piano duos). Studies of ensemble performance have focused on the coordination of sounds (i.e., audio or digital signals from acoustic or electronic instruments) and body movements (recorded with motion tracking systems) because these different sources of information about interpersonal synchrony potentially play complementary roles in communicating musical structure and expression.

Musical synchronization is a skill that needs to be developed. The roots of musical synchronization can be found in the vocal and gestural exchanges that characterize mother-infant interaction. Basic social interaction abilities acquired during the first three years of life are gradually transformed into skills that allow children to achieve the fine temporal precision required for sensorimotor synchronization in musical contexts. Infants aged 5 to 24 months adjust the speed of their spontaneous body movements in response to changes in musical tempo, and at 2.5 years of age, children are able to synchronize to some degree with pacing sequences that are close to their spontaneous motor tempi (i.e., the rate at which a child chooses to tap a finger or beat a drum when asked to do so without a pacing sequence).

Children of this age are drawn away from their spontaneous motor tempi when asked to beat a drum together with a human drumming partner, but not with a drumming robot or a recording of drum sounds, pointing to social origins of sensorimotor synchronization. The flexibility required for precise sensorimotor synchronization with different types of pacing sequences (social versus nonsocial; metronomic versus rhythmically varying) at a range of tempi, however, does not develop until around 5 years of age. This ability improves between 6 and 15 years, and then remains stable until old age.

Synchronization in musical contexts involving instrumental performance and dance serves a variety of social functions. Interpersonal synchrony creates the impression of unison action, and thus signals intimacy between individuals in small groups and social cohesion among members of larger groups. Psychological research on the social effects of interpersonal synchrony has shown that rhythmic coordination between individuals promotes interpersonal affiliation, bonding, trust, commitment, and cooperative behavior. Potential causes of these prosocial effects include the blurring of the psychological distinction between "self" and "other," the positive enhancement of emotional state through activation of the brain's reward system (by stimulating the release of the neurotransmitter dopamine), and the modulation of levels of hormones that influence social behavior (e.g., oxytocin and testosterone).

Biological Factors

The evolutionary origin of the human capacity for musical synchronization is a vigorously debated topic. Several species of nonhuman animals engage in synchronous behavioral displays, including fireflies that emit bioluminescent flashes in the night, fiddler crabs that wave their oversized claws, and crickets and frogs that chorus in unison. None of these displays, which are produced by males to attract females, possess the high degree of flexibility in terms of tempo and diversity of body movements that characterizes interindividual synchronization in human music making and dance. There have, however, been reports of relatively flexible sensorimotor synchronization abilities in animal species capable of vocal learning (e.g., parrots), suggesting that musical synchronization may capitalize on auditory-motor brain networks that originally evolved to support vocal imitative behavior serving social functions.

Research in neuroscience has employed a variety of brain imaging methods to identify the cerebral structures and functional mechanisms that support musical synchronization. Studies using techniques to measure cerebral blood flow have revealed that musical synchronization is not controlled by a single, dedicated brain region, but rather by a globally distributed network of regions. Even in the simplest case of sensorimotor synchronization with metronomic auditory sequences, this brain network comprises multiple cortical areas (including the primary motor cortex, premotor cortex, supplementary motor area, and the superior temporal gyrus) and subcortical structures (basal ganglia, thalamus, and cerebellum) that subserve sensory processing, beat extraction, motor control, and the coupling of sensory and motor processes. Additional brain regions (e.g., prefrontal areas associated with working memory and attention) are recruited during synchronization with complex rhythms and tempo-changing sequences.

Neural entrainment is the fundamental brain mechanism that drives synchronous behavior. Electrophysiological techniques with high temporal resolution—electroencephalography (EEG), where electrical signals reflecting neural activity are recorded from the scalp, and magnetoencephalography (MEG), where related changes in magnetic fields are recorded—have been used to study how neural oscillations in an individual's brain entrain to periodicities that are perceived in external rhythmic events. Research that is relevant to musical synchronization has focused on patterns of neural entrainment associated with perception of the beat (tactus or pulse, i.e., the most salient level of periodicity) in acoustic signals. This work has identified beat-related modulations in oscillatory activity in different EEG and MEG frequency bands (20–30 Hertz beta waves and 30–60 Hertz gamma waves), as well as evidence for hierarchical patterns of neural entrainment at the beat and higher metric levels in EEG steady-state evoked potentials (i.e., peaks at specific frequencies in the EEG power spectrum). Recent research has employed dual-EEG setups to explore neural signatures of interpersonal synchrony by measuring the entrainment of neural oscillations in two co-acting individuals' brains during musical duet performance and other rhythmic coordination tasks.

Musical synchronization has proven effective in the rehabilitation of physical and social-emotional clinical disorders. Techniques involving synchronous behavior have been associated with positive outcomes in music therapy (e.g., for children with autism) and in the rehabilitation of cognitive disturbances (e.g., dementia and aphasia following stroke) and motor disorders (e.g., Parkinson's and Huntington's disease) caused by brain damage. For example, providing an external auditory pacing sequence while walking can alleviate disturbances to the gait of Parkinson's patients. Recent work suggests that the benefits of such auditory cuing—where sounds stabilize the control of movement through auditory-motor coupling—are heightened when the strength of coupling is increased by programming the pacing sequence to adapt to the patient's timing. The potential for musical synchronization to promote health and well-being is a rapidly growing area of interdisciplinary research.

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See Also: Dance; Dementia; Drumming; Electronic Music; Ensemble Performance; Expressive Timing; Meter; Movement; Parkinson's Disease; Rhythm; Tactus and Pulse; Tempo; Timing.

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