Theories of pain: from specificity to gate control

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Moayedi M, Davis KD. Theories of pain: from specificity to gate control. J Neurophysiol 109: 5–12, 2013. First published October 3, 2012; doi:10.1152/jn.00457.2012.—Several theoretical frameworks have been proposed to explain the physiological basis of pain, although none yet completely accounts for all aspects of pain perception. Here, we provide a historical overview of the major contributions, ideas, and competing theories of pain from ancient civilizations to Melzack and Wall’s Gate Control Theory of Pain.

painless control; medicine; Descartes; specificity; labeled line; pattern theory; somatosensory

IT IS A SHAME THAT WE POSSESS such insufficient knowledge concerning the character of pain—those symptoms which represent the essential part of all bodily suffering of man (Goldsheider 1894).

The current definition of pain, established by the International Association for the Study of Pain (IASP) in 1986, defines pain as “an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of tissue damage, or both.” This definition is the culmination of centuries of ideas and work that have explored the concept of pain.

A number of theories have been postulated to describe mechanisms underlying pain perception. These theories date back several centuries and even millennia (Kenins 1988; Perl 2007; Rey 1995). This review will mainly focus on theories postulated since the 17th century and then provide an overview of current thinking. The four most influential theories of pain perception include the Specificity (or Labeled Line), Intensity, Pattern, and Gate Control Theories of Pain (Fig. 1).

SPECIFICITY THEORY OF PAIN

The Specificity Theory refers to the presence of dedicated pathways for each somatosensory modality. The fundamental tenet of the Specificity Theory is that each modality has a specific receptor and associated sensory fiber (primary afferent) that is sensitive to one specific stimulus (Dubner et al. 1978). For instance, the model proposes that non-noxious mechanical stimuli are encoded by low-threshold mechanoreceptors, which are associated with dedicated primary afferents that project to “mechanoreceptive” second-order neurons in the spinal cord or brainstem (depending on the source of the input). These second-order neurons project to “higher” mechanorece-
sensory cue (Descartes et al. 1664). A sensory cue would “tug” on the tube, which would then open a gate between the tube and the brain. The opening of this gate would then allow “animal spirits” (an extension of the Greek pneuma4) to flow through these tubes and within the muscles to move them. Although this sensory system was not specific to pain, La Forge’s drawing (based on Descartes’ concept and La Forge’s understanding of contemporaneous anatomy) of a foot near a flame is one of the most famous figures in neuroscience (Fig. 2). This example describes the pathway for promptly moving one’s foot away from a hot flame. In the figure (and its description in the text), the heat of the flame near the foot activates a fibril (or fiber) within the nerve tubule that traverses up the leg, to the spinal cord, and finally, to the brain. Descartes compared this fiber with a cord attached to a bell—by pulling on the other end of cord, the bell will ring. The proverbial bells, in this case, are the pores that line the ventricles in the brain. Once these pores open in response to the sensory input, the animal spirits were thought to flow through the tubule and elicit a motor response. This motor response included turning the head and the eyes to see the flame and raising the hands and folding the body away from the flame for protection. Descartes conceived that there are many of these fibrils and that their movements elicit the sensations. For example, the perception of pain would be felt in the brain when there is a significant tug on the fiber, which caused it to sever. In contrast, a tug of the same magnitude that does not cause the fiber to break would evoke a tickling (or tingling; Descartes uses the French word chatoullement) perception. Although La Forge’s figure of the boy and the flame suggests that there is a dedicated pain pathway, a closer read of the text indicates that Descartes believed that the pattern and rate of firing (intensity of tugging) of a fiber provided the adequate information to the brain about the stimulus intensity and quality. In fact, it is likely that the misconception of a dedicated pathway in the somatosensory system by Descartes is an extension of his proposal that the visual system requires a labeled line (where the image is carried and projected in the brain).

Anatomical discoveries inform physiology. The modern concept of a dedicated pain pathway (also known as Specificity Theory; see Fig. 1A) was developed by Charles Bell in his landmark essay, Idea of a New Anatomy of the Brain, submitted for the observation of his friends, first published as a conference proceeding in 1811 and later reproduced in a journal (Bell

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4 In ancient Greek medicine, the concept of pneuma represents air, breath, or motion. It was also called the breath of life and the spirit of man (Stead 1998).
and from the spinal cord (the ventral and dorsal roots, respec-
tively) (Stahnisch 2009). This differentiation of spinal nerves is
known as the Bell-Magendie Law, which is a fundamental
aspect of the organization of the nervous system.

Concurrently, in Germany, Johannes Müller published a
Manual of Physiology, which echoed Charles Bonnet’s manual
published one century earlier (Rey 1995). Müller’s manual,
published in 1840, sought to summarize and synthesize find-
ings in physiology. The purpose of this synthesis was to
understand how different stimuli were so clearly sensed and
how the brain could distinguish them from one another. He,
like Bonnet, concluded that specific receptors must have spe-
cific energy of stimulation and that there were infinite numbers
and types of fibers, each to a specific sensory stimulus; e.g.,
there is a specific fiber for the smell of bananas, another for the
scent of an apple, and yet another for the scent of an orange.
Furthermore, because of a sense organ’s specific energy, the
sensory neuron will only encode a single perceptual quality.
For example, if a warm fiber is artificially stimulated by an
electric current, the brain will perceive warmth. In line with
these findings, Erasmus Darwin (Charles Darwin’s grandfa-
ther) provided the first evidence for a set of specific nerves for
the perception of heat (Darwin and Darwin 1794).

The discovery of specific, cutaneous touch receptors, such as
Pacinian corpuscles [Pacini 1835; cited in Cauna and Man-
man (1958)], Meissner’s corpuscles [Meissner 1853; cited in Cauna
and Ross (1960)], Merkel’s discs [Merkel 1875; cited in Cauna
and Mannan 1958], and Ruffini’s end-organs (Ruffini 1893), in
the latter one-half of the 19th century, provided further evi-
dence that specific sensory qualia were encoded by dedicated
nerve fibers. However, there remained a debate about the
nature of pain as part of the five senses, as an end-organ
specific to pain stimuli (nociceptor) had not yet been discov-
ered. In contrast to the idea of a dedicated pain pathway, it was
argued that pain was different than the other senses in that it is
inherently unpleasant (Boring 1942; Dallenbach 1939). These
ideas persisted from Plato’s and Aristotle’s writings of pain as
an emotion (Schmitter 2010). This inherently makes pain the
antithesis of pleasure, and because pleasure is a characteristic of the mind (i.e., an emotion), it was inferred that pain was also a characteristic of the mind and not a percept of the body.

Further evidence for the Specificity Theory came from Schiff and Woroschiloff’s findings of a pain pathway in the spinal cord in a series of experiments between 1854 and 1859 (Rey 1995). These findings built on Charles-Édouard Brown-Séquard’s observations that sensory fibers decussate in the spinal cord (Aminoff 1996; Dallenbach 1939). Schiff and Woroschiloff established the presence of two pathways through observations of the effect of incisions at different levels of the spinal cord: the anterolateral pathway for pain and temperature and the posterior bundles for tactile sensibility (Dallenbach 1939; Rey 1995). However, Schiff and Woroschiloff noted that the tactile pathway did not decussate at the level of the spinal cord. These findings were supported by a case study by William Richard Gowers, a physician in London, who reported that a patient with a bullet wound to the gray matter of the spinal cord lost the sense of pain and temperature but not touch (Rey 1995). He concluded that there were specific pathways for pain and temperature, separate from that of touch. However, those who held onto the Aristotelian dogma argued strenuously against the Specificity Theory. They insisted that pain is a quality of all senses—a percept of the mind. Only when Blix and Goldscheider published their findings of sensory spots on the skin independently did the Specificity Theory gain momentum and did pain become a recognized sense (Dallenbach 1939). Sensory spots were defined as tiny areas of the skin that elicit a specific sensation when touched. These sensory spots were specific to warmth, cold, pressure, or pain. However, both Blix and Goldscheider moved away from the Specificity Theory some years later and moved toward the Intensity Theory of Pain, a concurrent theory (see below).

von Frey’s and Goldscheider’s skin spots. Between 1894 and 1896, Max von Frey carried out experiments that advanced the Specificity Theory (Rey 1995). von Frey indicated that there were four somatosensory modalities: cold, heat, pain, and touch and that all of the other skin senses were derivatives of these four modalities. To test this idea, he developed his now well-known “von Frey hairs” (termed an aesthesiometer), which consisted of a hair—usually from a human, but sometimes he used a horsehair or a hog bristle—attached to a wooden stick (Perl 1996). By measuring the hair’s diameter, length, and precise maximal weight that it could support without breaking off of the stick (maximal tension), it was possible to measure the force applied to a very specific spot. Today, von Frey hairs are made of fine nylon filaments of varying thicknesses (and hence, stiffness to deliver different forces and pressures upon bending). With the use of these hairs, he could carefully determine the pressure required to elicit a sensation at each of the skin spots identified by Blix and Goldscheider. Furthermore, his experimental setup allowed him to determine which spots responded to innocuous pressure and which ones responded to noxious pressure. von Frey demonstrated that there were distinct spots for innocuous pressure and for noxious pressure. He presented a model of the skin that comprised a “mosaic of distinct tactile, cold, warm, and pain spots distributed across the skin with distinctive regional variation” (Perl and Kruger 1996). von Frey related the distribution of the pressure points to the distribution of Meissner’s corpuscles, whereas pain points were related to the distribution of free nerve endings in the skin. Despite these remarkable findings, the Specificity Theory made a number of assumptions about the anatomical, physiological, and psychological bases of somesthesia and pain. For instance, when von Frey postulated the theory, pain receptors had yet to be identified nor were the peripheral pathways and brain centers specific to pain sensation established, as well as other factors [for a review, see Dallenbach (1939) and Rey (1995)].

Landmark discoveries. Charles Scott Sherrington (1947) addressed some of the assumptions of the Specificity Theory in his proposed framework of nociception. He applied a Virchowian (i.e., based on the cell theory) and Darwinian (i.e., evolutionary) approach to study integration in the nervous system. Specifically, he examined what he conceived to be the functional basic unit (the simple reflex arc) to understand the nervous system. With the use of this method, he described the specificity of neurons, which included the four basic modalities recognized by von Frey. Furthermore, he postulated that behavior in animals is the temporal and spatial pattern of activity, resulting from the interaction of these specific neurons. His studies allowed him to conclude that “the main function of the receptor is [. . .] to lower the excitability threshold of the [reflex] arc for one kind of stimulus and heighten it for all others” (Sherrington 1906, 1955). This “selection” approach resolved the divide between the Intensity Theory (see below) and Specificity Theory (Rey 1995), because it accounts for findings of specific pain points (i.e., receptors that are specific to pain) and also accounts for the Intensity Theory (i.e., somatosensory stimulation, which is intense or excessive, activates the pain reflex arc because this is its common feature). He also coined the term “nociceptor” (Sherrington 1903) to describe the specificity of the cutaneous end-organ for noxious stimuli, later termed nociceptor (Sherrington 1906). Sherrington developed a framework that advanced the Specificity Theory of Pain even further. However, the nociceptor had yet to be identified definitively.

The discovery of myelinated primary afferent fibers that respond only to mechanical noxious stimuli occurred much later, in 1967 (Burgess and Perl 1967). Soon thereafter, Bessou and Perl (1969) discovered nociceptive, unmyelinated afferent fibers: polymodal nociceptors and high-threshold mechanoreceptors. These findings revolutionized the field of pain research and helped advance and develop a number of theories of pain. Since Sherrington’s endorsement of the Specificity Theory of Pain, this became the dominant theory at the time. However, its popularity waned with the postulation of the Gate Control Theory of Pain (see below) by Melzack and Wall (1965).

INTENSITY THEORY OF PAIN

An Intensive (or Summation) Theory of Pain (now referred to as the Intensity Theory) has been postulated at several different times throughout history. First, conceptualized in the fourth century BCE by Plato in his oeuvre Timaeus (Plato 1998), the theory defines pain, not as a unique sensory experience but rather, as an emotion that occurs when a stimulus is stronger than usual. Centuries later, Erasmus Darwin (Darwin and Darwin 1974) reiterated this concept in Zoonomy. One hundred years after Darwin, Wilhelm Erb also suggested that pain occurred in any sensory system when sufficient intensity was reached rather than being a stimulus modality in its own
right [cited in Dallenbach (1939)]. Arthur Goldscheider further advanced the Intensity Theory, based on an experiment performed by Bernhard Naunyn in 1859 [cited in Dallenbach (1939)]. These experiments showed that repeated tactile stimulation (below the threshold for tactile perception) produced pain in patients with syphilis who had degenerating dorsal columns. When this stimulus was presented to patients 60–600 times/s, they rapidly developed what they described as unbearable pain. Naunyn reproduced these results in a series of experiments with different types of stimuli, including electrical stimuli. It was concluded that there must be some form of summation that occurs for the subthreshold stimuli to become unbearable painful. Goldscheider suggested a neurophysiological model to describe this summation effect: repeated subthreshold stimulation or suprathreshold hyperintensive stimulation could cause pain (see Fig. 1B). He suggested further that the increased sensory input would converge and summate in the gray matter of the spinal cord. This theory competed with the Specificity Theory of Pain, which was championed by von Frey. However, the theory lost support with Sherrington’s evolutionary framework for the Specificity Theory and postulated the existence of sensory receptors that are specialized to respond to noxious stimuli, for which he coined the term “nociceptor.”

PATTERN THEORY OF PAIN

In an attempt to overhaul theories of somaesthesia (including pain), J. P. Nafe postulated a “quantitative theory of feeling” (1929). This theory ignored findings of specialized nerve endings and many of the observations supporting the specificity and/or intensive theories of pain. The theory stated that any somaesthetic sensation occurred by a specific and particular pattern of neural firing and that the spatial and temporal profile of firing of the peripheral nerves encoded the stimulus type and intensity (see Fig. 1C). Lele et al. (1954) championed this theory and added that cutaneous sensory nerve fibers, with the exception of those innervating hair cells, are the same. To support this claim, they cited work that had shown that distorting a nerve fiber would cause action potentials to discharge in any nerve fiber, whether encapsulated or not. Furthermore, intense stimulation of any of these nerve fibers would cause the percept of pain (Sinclair 1955; Weddell 1955).

GATE CONTROL THEORY OF PAIN

In 1965, Ronald Melzack and Charles Patrick (Pat) Wall (Melzack and Wall 1965) proposed a theory that would revolutionize pain research: the Gate Control Theory of Pain. The Gate Control Theory recognized the experimental evidence that supported the Specificity and Pattern Theories and provided a model that could explain these seemingly opposed findings. In a landmark paper, Melzack and Wall (1965) carefully discussed the shortcomings of the Specificity and Pattern Theories—the two dominant theories of the era—and attempted to bridge the gap between these theories with a framework based on the aspects of each theory that had been corroborated by physiological data. Specifically, Melzack and Wall accepted that there are nociceptors (pain fibers) and touch fibers and proposed that these fibers synapse in two different regions within the dorsal horn of the spinal cord: cells in the substantia gelatinosa and the “transmission” cells. The model (see Fig. 1D) proposed that signals produced in primary afferents from stimulation of the skin were transmitted to three regions within the spinal cord: 1) the substantia gelatinosa, 2) the dorsal column, and 3) a group of cells that they called transmission cells. They proposed that the gate in the spinal cord is the substantia gelatinosa in the dorsal horn, which modulates the transmission of sensory information from the primary afferent neurons to transmission cells in the spinal cord. This gating mechanism is controlled by the activity in the large and small fibers. Large-fiber activity inhibits (or closes) the gate, whereas small-fiber activity facilitates (or opens) the gate. Activity from descending fibers that originate in supraspinal regions and project to the dorsal horn could also modulate this gate. When nociceptive information reaches a threshold that exceeds the inhibition elicited, it “opens the gate” and activates pathways that lead to the experience of pain and its related behaviors. Therefore, the Gate Control Theory of Pain provided a neural basis for the findings that supported and in fact helped to reconcile the apparent differences between the Pattern and Specificity Theories of Pain.

SHORTCOMINGS OF THE COMPETING PAIN THEORIES

Each of the major pain theories discussed in the previous sections adequately described a series of observations about the nociceptive system and pain perception. However, none adequately accounted for the complexity of the pain system. For instance, although the Specificity Theory appropriately described sensory receptors that are specific to nociceptive stimuli and primary afferents that show responses only to suprathreshold stimuli, it did not account for neurons in the central nervous system (CNS) that respond to both non-nociceptive and nociceptive stimuli (e.g., wide-dynamic range neurons). Although these neurons are well characterized, their function in pain perception has yet to be determined.

Another shortcoming of these theories is that they focus on cutaneous pain and do not address issues pertaining to deep-tissue, visceral, or muscular pains. Although Sherrington does discuss visceral and muscular pain (Sherrington 1947), these observations are not fully accounted for within his model. Additionally, these models are focused on acute pain and do not address mechanisms of persistent pain or the chronification of pain, likely because at the time, it was assumed that the nervous system was hard wired. Although the mechanisms of persistent and chronic pain are still not fully understood, it is now clear that peripheral and central plasticity can arise following repeated nociceptive stimulation in healthy subjects (Bingel et al. 2008; Teutsch et al. 2008) and in chronic pain [for a review, see Davis and Moayedi (2012)]. In addition, recent work has demonstrated that plasticity is not limited to changes in neurons but can also involve changes in glial cells (Eroglu and Barres 2010; Streit et al. 1988), which may relate to the maintenance of persistent and chronic pains (Scholz and Woolf 2007; Zhuo et al. 2011).

The Gate Control Theory is the most promulgated of pain theories and led to some of the most fruitful research in the field of pain. However, many of the details of this theory have been shown to be inaccurate. For example, there were over-simplifications and flaws in the presentation of the neural architecture of the spinal cord, the location and the model pertaining to how large afferent fiber stimulation inhibits or
modulates C-fibers (Nathan and Rudge 1974), and the hypoth-


