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A Biosemiotic Analysis of Braille

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Abstract A unique aspect of human communication is the utilization of sets of well-delineated entities, the morphology of which is used to encode the letters of the alphabet. In this paper, we focus on Braille as an exemplar of this phenomenon. We take a Braille cell to be a physical artifact of the human environment, into the structure of which is encoded a representation of a letter of the alphabet. The specific issue we address in this paper concerns an examination of how the code that is embedded in the structure of a Braille cell is transferred with fidelity from the environment through the body and into the Braille reader's brain. We describe four distinct encoding steps that enable this transfer to occur.

Keywords Braille · Encoding · Biosemiotic systems · Neuronal groups · Somatosensory system

Introduction

We are concerned in this paper with an examination of how the code that is embedded in the structure of a Braille cell is transferred from the environment through the body and into the brain of a Braille reader. Braille reading necessarily engages the tactile sensing components of the body and the somatosensory system of the brain. These factors make possible a close analysis of the code transfers involved

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in Braille reading, and allows us to identify four distinct steps that are components of a sequence of encoding processes that enable this transfer to occur.

When we use the phrase 'Braille reading', we are referring to the entire biosemiotic process embodied in Braille reading and not merely the point in time when that which is read becomes meaningful to the reader. Before the message encoded in any text can become meaningful, the code must first be transferred with great fidelity into the sensory systems of the reader's brain. By 'fidelity' we mean, for example, the necessity that in the transfer process a 'b' encoded in a code-entity (e.g., a Braille cell) in the environment is not represented as a 'd' in the brain. In the case of Braille, a text is composed of a series of Braille cells. We will later describe in detail the structure of Braille cells, but for now we can say that we take a Braille cell to be a physical artifact of the human environment. In the structure of this artifact there is encoded a representation of a letter of the alphabet. In the process of Braille reading, the code embedded in the structure of the Braille cell must be transferred into the Braille reader's brain, all the while preserving the essence of that which is embedded.

We know a good deal about human sensory systems, from the sensory receptors and associated sensory nerves, to the brain structures of the sensory systems (e.g. spinal cord and brainstem sensory nuclei, thalamic nuclei and primary sensory cortices). Also well understood is how various features of our environment such as electromagnetic and acoustic waves, and mechanical pressure applied to our skin, are processed by our visual, auditory, and somatosensory systems, respectively.

On the other hand, we know very little about how the code-entities (e.g., letters of the alphabet in written or Braille texts), which are fundamental components of the biosemiotic systems used in language-based inter-human communication, are transferred from the environment through the body and into the brain. The code that is embedded in the structure of the Braille cell must become embedded in a neuronal structure, at which point it becomes a symbol for a letter of the alphabet. This is not a problem of sensory signal reception and transmission. It is a problem of code reception and transmission.

Symbols in Biology

We intend this paper to further the analysis of the significance of symbols in biology, which was the focus of two papers previously published in this journal. In the first paper we discussed how features of the environment of cells, both free-living and as components of multicellular organisms, become internally represented by organic molecules (e.g., second messengers, hormones, neurotransmitters) that serve both as symbols of significant external environmental features, and as drivers of adaptive responses (Swan and Goldberg 2010a). In the second paper, we extended the analysis to the rat, a complex animal, to show how subtle environmental features can be represented as symbols in the rat brain's somatosensory system (Swan and Goldberg 2010b). The formation of these symbols provides the necessary ground for the adaptive responses of the animal to significant environmental features.

In the present paper, we extend the analysis to humans to show how Braille cells become symbols in the somatosensory system of the Braille reader's brain. We emphasize the unique structural characteristics of language-based code entities, e.g.,

the letters of the alphabet, and the unique problems involved in grounding such environmental features as symbolic representations in the human brain.

It is only humans that have the capacity to represent encoded alphabetic, environmental entities such as Braille cells as symbols in their sensory systems. We will show that the manner in which this occurs is an extraordinary example of the unique, epigenetic way in which code-entities of the human language biosemiotic system are transmitted from the environment through the structure of the body and brain. The paper is about the nature of this essential, initial, symbol-grounding component of Braille reading.

The Braille Alphabet

We will examine the manner in which the Braille code links the alphabetic system of written letters with the readers' brains. Braille is a well-established method designed to permit blind people to read. In Braille, the alphabet is written in the form of Braille cells, which are features of the reader's environment. Braille cells are small, flat, rectangular objects of a standard size. Within the rectangle are six, symmetrically arranged locations. The surface of each location can either be flat or raised into projections that are called 'dots'. Each letter of the alphabet is uniquely represented in Braille cells by the pattern formed by the particular location of the dots in the six possible locations. The alphabet written in Braille cells is shown in Fig. 1.

An individual with no experience reading Braille who ran his index finger pad over Braille cells in the particular configuration shown in Fig. 1 would report that he had encountered a rough surface, just as an individual ignorant of written language would see this page you are reading as a white surface covered with black markings.

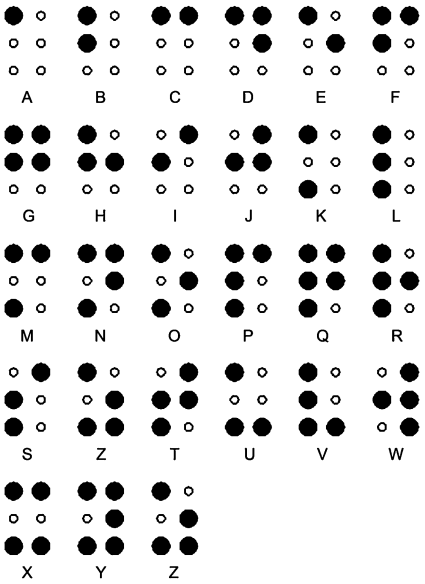

Fig. 1 The English alphabet illustrated in Braille cell morphology. *Open circles* indicate the six dot positions in each cell. Large, *filled circles* indicate raised dots. The following measures of Braille cell dimensions are those adopted by the American Library of Congress: the distance between dots is 2.5 mm; the distance between cells is 6.0 mm; raised dots (*filled circles*) project 0.5 mm above the surface; dot base diameter is 1.5 mm

But a Braille reader who ran her index finger pad over Braille cells in the particular configuration shown in Fig. 1 would report encountering the alphabet.

We are interested in understanding how the coded morphological characteristics of Braille cells become represented in the brain of the human reader. We aim to show in the following sections that the formation of such representations is dependent upon a cascade of several distinct steps, each of which constitutes a specific act of encoding.

Four Encoding Steps in the Transfer of Braille Cell Morphology to the Brain Somatosensory System

Step 1: The Encoding of Braille Cell Morphology in the Structure of the Finger Pad

The human finger pad is a soft, resilient structure. It acts as a cushion when objects are gripped by the hand and it acts a sensor for the texture, temperature and pressure of objects with which it comes in contact. In Braille reading, the finger slides from one Braille cell to another with the application of sufficient downward pressure to allow the raised dots to mechanically compress the pad, forming an extremely brief patterned impression in the finger pad. The crucial insight here is that the representation of a letter of the alphabet encoded in the particular pattern of raised dots of any given Braille cell is conserved when transformed into a particular pattern of indentations on the finger pad.

This is the first encoding event in the process of Braille reading. The Braille cell is an object that has the capacity to endure for a period of time measured in years; yet the indented, patterned compression on the finger pad endures for a period of time measured in milliseconds (ms). As will be described in more detail in a later section, during the activity of reading Braille, the finger pad makes contact with a new Braille cell approximately every 200 ms. The particular patterns of finger pad impressions are continuously eliminated from the finger pad as it springs back to its original state, ready to encounter the next cell.

Step 2: The Encoding of Finger Pad Morphology to the Mechanoreceptor Grid in the Underlying Finger Pad Dermis

In Step 2, another transfer of the morphology of the Braille cell takes place. This is realized by the encoding of the patterned impressions on the finger pad to the activation of mechanoreceptors called Meissner's corpuscles (MCs) located in the dermis underlying the skin of the pad. This step constitutes another example wherein the relevant structural component changes while the morphological pattern is conserved.

A brief description of the mechanoreceptor grid follows in order to emphasize that the encoding process is completely organic and instantiated in structures and processes that evolved long before the advent of language. Below the skin of the finger pad there exists a fine-grained grid of mechanoreceptors (Bolanowski and Pawson 2003; Phillips et al. 1992). The standardized dimensions of the Braille cell developed over time through a trial-and-error process that was constrained by the

operational characteristics of this grid. The determining factors that resulted in the dimensions of the dots and the distance between them were the size of the human index finger pad, and the number and density of the mechanoreceptors located in the dermis of the pad. An illustration of the mechanoreceptor grid is shown below in Fig. 2.

MCs, structures that are "between 40 and 70 μm in diameter and between 100 and 150 μm in length" are "small, encapsulated, sensory receptors found in the dermis of the skin, particularly of the fingertips...[that] are involved in the reception of light discriminatory touch, the degree of discrimination depending on the proximity of receptors to one another" (Bolanowski and Pawson 2003).

In the act of Braille reading, the finger pad is a scanner for tactile stimuli. The Braille cell dots must be placed at a sufficient distance from each other so that each raised dot can be clearly discriminated from its neighbors, but close enough so that the entire six dot array can fit into the scanning field of the finger pad. When a raised dot presses on the finger pad, it causes a local mechanical deformation of the pad that compresses and therefore activates MCs. The circumference of the tip of the dot is smaller than that of its base and will therefore compress a smaller area. The fact that Braille readers are able to distinguish one Braille cell from another solely on the basis of distinguishing the pattern of raised dots in the cell indicates that inter-dot spatial separation is sufficient to support their discrimination.

It is clear that Braille cell morphology has been shaped by the morphology of the human finger pad, and by the density and distribution characteristics of the pad's underlying field of mechanoreceptors. It is safe to say, however, that finger pads did not evolve so that blind humans could read Braille. It is a clear case of exaptation (Gould and Vrba 1982): the highly developed tactile sensitivity of primate finger

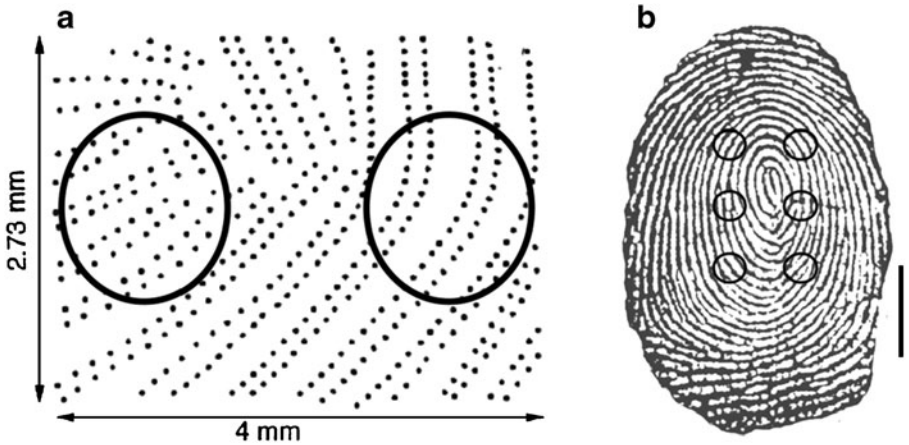

Fig. 2 [A modification of Fig. 9 in Bolanowski and Pawson 2003.] **a** shows the organization of the mechanoreceptors called Meissner's corpuscles (MCs) in a small section of the index finger pad of a macaque monkey. Each point represents one MC. The organized rows of MCs associated with fingerprint ridges can be seen. The *large circles* represent the circumferences of two Braille dots. **b** shows an image of a human fingerprint with an overlay of a Braille cell. The *circles* represent the six dot positions of a Braille cell. It can be seen in **b** that the entire Braille cell fits easily within the scanning zone of the pad of an index finger. [*Calibration bar* in B is 4 mm.]

pads has now come to serve as an essential component of the completely new function of Braille reading.

Step 3: Mechanoreceptor Grid Activation is Encoded as Patterns of Activity in Specific Sets of Sensory Nerves of the Somatosensory System

In this step, the code moves from the mechanoreceptor grid of the finger pad to the peripheral sensory nervous system and ultimately to the central nervous system. In order for Braille reading to occur, the compression pattern on the grid must, at this point, move from its location on the periphery of the body to the cervical spinal cord of the brain, a distance of about 1 m in the adult human.

Interwoven among the cells that form the MC are the peripheral endings of sensory neurons. Processes initiated by mechanical compression of an MC lead to excitation of the sensory nerve endings and the production of electromagnetic waves (action potentials) that travel toward the central nervous system along sensory nerve fibers. The evidence suggests that, for the most part, each MC is associated with one sensory neuron (Phillips et al. 1992). This step constitutes yet another structural transfer of the conserved encoded information wherein the mechanical energy that distorts the pad and compresses MCs is converted into the electrochemical energy of the action potentials (electrochemical waves that flow along the axons of sensory neurons from the periphery to the brain). For a Braille cell to eventually be decoded and recognized as a particular letter of the alphabet, the steps outlined in 2.1–2.4 must first occur (see Fig. 3).

If the grounding phase of Braille reading semiotic system is to work, the representation of the letters encoded into the morphology of the Braille cell must be transferred with fidelity into the brain. In the step under consideration here, the encoding occurs in the form of a spatiotemporal entity. The spatial character of the encoded message exists in the specific pattern of nerve fibers that are stimulated by the configuration of each Braille cell. The temporal character of the entity is the synchronous wave of electrochemical flow that is carried by the specific set of nerve fibers. These fibers conduct at speeds on the order of 50 m/s and so the approximately 1 m distance between the finger pad and the spinal cord is traversed in about 20 ms. Once the wave has passed, the nerve fibers become silent and the spatiotemporal entity ceases to exist.

We stress again that in our analysis we are interested in the problem of tracking the steps by which representations encoded into the morphology of Braille cells are encoded into the somatosensory system of the brain. The steps described up to this point all involve a process of encoding that transfers the code from one entity to the next.

Step 4. Sensory Nerve Input in the Somatosensory System is Encoded as Neuronal Groups

The Somatosensory System and Braille

It is necessary for us now to show that a further transfer of morphology occurs when the electrochemical flow in the sensory fibers enters the central nervous system. In

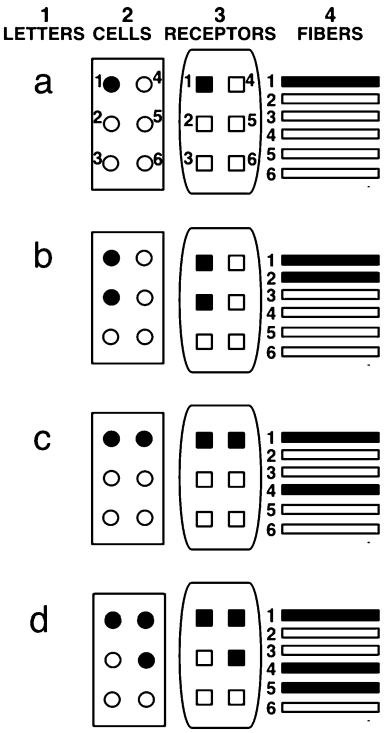

Fig. 3 A diagram illustrating the steps in the transfer of Braille cell morphology to the finger pad, mechanoreceptor grid, and sensory nerve fibers. *Column 1*) the first *four letters* of the alphabet in written script. *Column 2*) those *letters* of the alphabet encoded in Braille cells. The *numbers* next to the Braille cell dots in the top two rows indicate the conventional numbering of Braille cell dot location. *Black-fill* indicates raised dots. *Column 3*) the *squares* indicate the compression of the finger pad MCs by the raised dots of the corresponding Braille cell. *Filled black squares* indicate locations on the grid that have been compressed by raised dots. *Column 4)* the pattern of input into the central nervous system carried by nerve fibers stimulated by the compressed mechanoreceptors shown in Column 3. *Numbers* on the left side of the bars in Column 4 correspond to the conventional numbering of Braille cell dot location and indicate that specific sensory fibers will be activated by corresponding raised dot locations on the Braille cell

this step, we hypothesize that there occurs the creation of neuronal entities—what Edelman refers to as neuronal groups, and what we have previously called *brain-objects* (Swan and Goldberg 2010b)—that encode in their structure a representation of the morphology of Braille cells.

Evidence for the Existence of Neuronal Groups

In his book, *Neural Darwinism*, Gerald Edelman makes a strong case for the presence in the brain of entities he refers to as 'neuronal groups'. These groups of neurons are "dynamically" selected from much larger networks of neurons. According to Edelman, neuronal groups are the key to understanding how the mammalian brain is able to faithfully represent features of an unpredictable, ever changing environment (Edelman 1987). In a previous paper we went into great detail explaining the formation of neuronal groups in the coding of somatosensory information in an animal model (Swan and Goldberg 2010b). Suffice it to say here,

however, that neuronal groups are composed of hundreds to thousands of neurons that have been selected from much larger interconnected networks of tens of thousands of neurons. The neurons are epigenetically selected by a dynamic, Darwinian process that Edelman called the Theory of Neuronal Group Selection (TNGS) (Edelman 1987).

Figure 4 is an illustration of the encoding steps we have described up to this point, including the step of encoding Braille cell morphology into neuronal groups in the somatosensory system.

Stringent conditions must be met for the formation of neuronal groups. According to Edelman, "similar or identical signals" must be presented frequently at the same location (Edelman 1987). Braille reading meets all three of these criteria of the signals being: 1) identical; 2) at the same location; and 3) frequently presented. One of the conditions necessary for Braille reading is the morphological consistency of the Braille cells (see Fig. 1). The finger pad, generally of an index finger, is the consistent location for receiving the signal, and learning to read Braille requires the frequent and repetitive pressing of the finger pad on each of the various Braille cells before they eventually can be distinguished rapidly and with high accuracy.

On this view, successful selection of a neuronal group from tens of thousands of neurons in a network is dependent upon altering the synaptic efficacies among neurons in the network "so that there is an increased probability of their response to similar or identical signals" (Edelman 1989), which can only occur when such signals are presented frequently at the same location. Under these conditions, "dynamically selected neuronal groups are established" (ibid). The neuronal groups

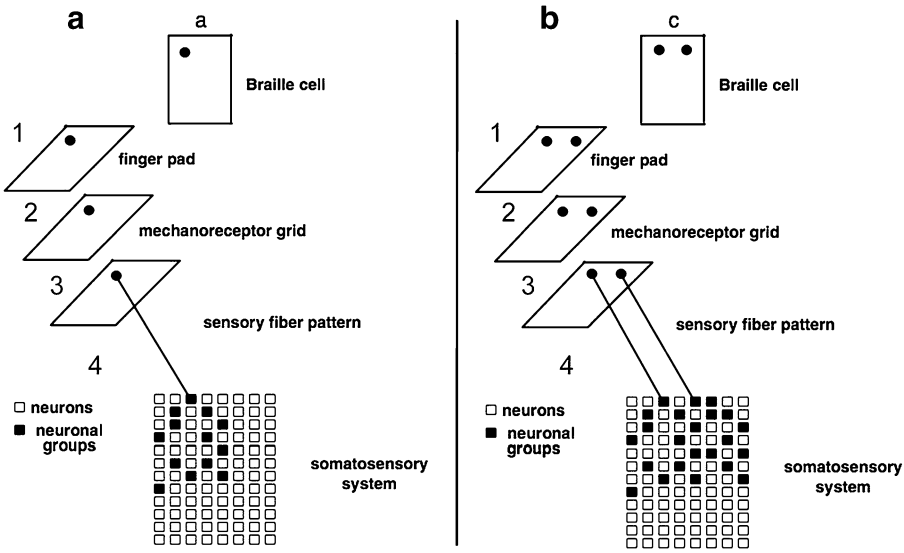

Fig. 4 **a** is an illustration of the transfer of the morphology encoded in the Braille cell for the letter '**a**'. **b** shows the transfer for the letter '**c**'. *Steps 1–4* show the transfer, or encoding, involved at the level of: *1*) the finger pad; *2*) the mechanoreceptor grid; *3*) the sensory fibers; and *4*) the somatosensory system. The *open squares* represent the interconnected neurons of the tens of thousands of neurons in the somatosensory system. *Filled squares* in **a** represent the subset of neurons that constitute the neuronal groups for the letter '**a**'. In **b**, a different neuronal group is formed when the Braille cell is encoded for the letter '**c**'

illustrated in Fig. 4, A1 and B1, will only form over time after one's finger pad is repeatedly stimulated by the Braille cells for 'a' and 'c'.

In Edelman's view, neuronal groups are formed "through epigenetic modifications in the strength of synaptic connections" among neurons in the network. These selected neuronal groups are composed of "collections of hundreds to thousands of strongly interconnected neurons" which act as "functional units" that are "correlated with various signals" from the environment (ibid). In our view, the fourth step is the formation in the somatosensory system of distinctive neuronal groups, with each neuronal group encoding at the level of the brain the morphology of a particular Braille cell.

The Temporal Dimension of the Four Encoding Steps Illustrated in Fig. 4

Terrance Deacon writes that the representation of encoded language symbols "demands both rapid implementation and an ability to keep previous operations from interfering with subsequent operations" (Deacon 1997). Because of these demands he postulates that "we must be able to 'offload' a significant part of the lower-level analysis...to some remarkably facile automatic systems" (ibid). These automatic systems would involve "millisecond-by-millisecond information processing that... adapt[s] neural software to the world" (ibid). We believe that the steps we have described here involving the transfer of the morphology of Braille cells through the body into the brain is an example of such a lower-level processing system. We will now examine this system, millisecond-by-millisecond.

Rapid Implementation and Avoidance of Interference

In Grade 1 Braille, each word is spelled out in Braille cells, letter for letter (Legge et al. 1999). Legge et al. report that the mean Grade 1 reading rate is approximately 60 words/minute, 5 characters (letters)/second and 12 dots/second.[1] For someone reading at a rate of approximately 60 words per minute using Grade 1 Braille, and assuming that each word is composed of an average of 5 letters, the finger would have to contact 300 cells every minute, or five cells every second, or one cell every 200 milliseconds. The questions to be answered are the following: do the four encoding steps described above occur rapidly enough to match the rate at which reading occurs, and can these encoding steps occur while keeping "previous operations from interfering with subsequent operations"? (Deacon 1997).

We have described a cascade of four encoding steps involved in transferring the information from the Braille cell into the somatosensory system of the brain. The temporal dimensions of the sequence of steps are illustrated in Fig. 5.

Steps 1&2: *Compression of the finger pad and activation of the grid.* Studies in humans have shown that the first action potentials in the sensory nerve begin approximately 20 ms after compression of the finger pad (Knibestol 1972).

[1] It is interesting to note that the authors report on the *number of dots per second* as a measure of speed in Braille reading, since this number is not essential to the overall process of reading Braille meaningfully. What is essential is the *pattern* of raised dots in Braille cells.

Step 3: *Conduction of the pattern of sensory nerve activity from the grid to the spinal cord.* The duration of the wave evoked by the mechanoreceptors in the sensory nerves is approximately 20 ms long and is in the form of a spike train of approximately 4 to 5 spikes. The spikes are action potentials that endure for 2 ms each, and the inter-spike intervals average approximately 4 ms to 5 ms (ibid). This package of spikes in the specific sensory nerve fibers associated with compressed mechanoreceptors—illustrated in the gray box in Fig. 5—travels from the finger pad to the spinal cord at an approximate speed of 50 m/s. This means that first spike of the sensory wave would reach the spinal cord approximately 20 ms after activation of the grid and the last spike of the wave would occur 20 ms later.

Step 4: *The relationship of the encoding transfers from the finger pad, to the grid, to the sensory nerves, to the somatosensory system in the brain is illustrated in Figs. 3 and 4.* The spike trains begin to enter the somatosensory system approximately 60 ms after the finger pad is compressed by a Braille cell and continue to arrive over the next 20 ms (Fig. 5). As the spikes move along the web formed by the synaptic interconnections of somatosensory neurons from spinal cord to thalamus to primary sensory cortex, they establish unique pathways leading to neuronal group formation (discussed above). These neuronal groups encode, in the central nervous system, the letters of the alphabet originally encoded in the morphology of the Braille cells.

Comparing the Latency of the Encoding Process to That of Electrical Stimulation of Finger and Arm

It has been demonstrated in electroencephalographic studies in humans that electrical stimulation of the finger results in the elicitation of neural activity in the somatosensory system (Niedermeyer and Da Silva 1999). These studies show that after strong electrical stimulation of the finger or median nerve in the arm, a

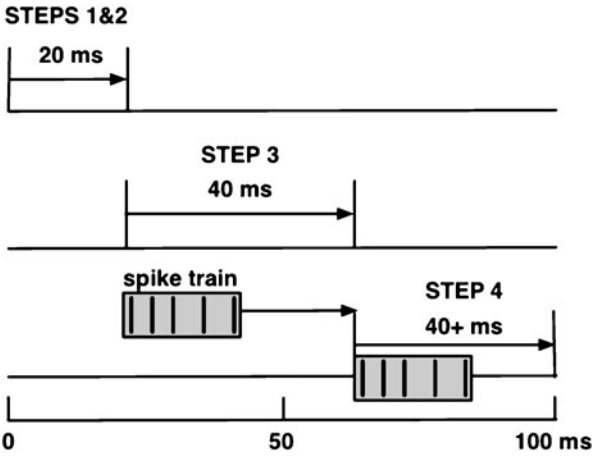

Fig. 5 An illustration of the time course of encoding steps from onset of finger pad compression at time 0, to the formation of neuronal groups in the somatosensory system of the brain. A more detailed description of Fig. 5 follows in the text below

synchronous waveform is recorded on the scalp with a latency of 18–30 ms. This waveform is thought to represent neuronal activity in the primary somatosensory cortex and possibly the thalamus.

In Fig. 5, we show sensory nerve activity arriving at the somatosensory system approximately 60 ms after stimulation of the finger pad and speculate that the activity in the neuronal groups of the somatosensory system, including the thalamus and primary somatosensory cortex, persists for a duration of at least another 50 ms, making the peak of neuronal ensemble activity occur after a latency of approximately 100 ms. Why is there a discrepancy between cortical latencies of 18–30 ms in the electrical stimulation studies and 100 ms in our encoding estimations?

We believe this discrepancy in latencies demonstrates a difference between simple sensation, and the complex encoding processes necessary for the transfer of Braille cell morphology into the human brain. In the study of Niedermeyer and Da Silva (1999) a strong single shock is delivered to the finger or the median nerve in the arm. There is no spike train. A single synchronous volley in every activated sensory nerve fiber travels from the stimulus site to the spinal cord, then to the thalamus and finally to the primary somatosensory cortex. This synchronous blast through the somatosensory system takes from 18 to 30 ms. In the case of Braille cell encoding, the process is completely different. The four step encoding process takes at least five times longer to reach the cortex than it does for a single, electrically stimulated volley. The person who is shocked feels a sensation with no subtlety, whereas the Braille cell reader is able to distinguish the subtle differences in Braille cell morphology.

The components of the finger pad, mechanoreceptor grid, and somatosensory system did not evolve for the purpose of enabling the initial, symbol grounding component of Braille reading as described above. In a remarkable case of *exaptation* these structures have been turned into a biosemiotic transfer system in which a letter of the alphabet that is encoded in the morphology of a Braille cell can be transferred from the body to the brain, where is it re-encoded in neuronal groups. All through this transfer process the information encoded in Braille cell patterns is preserved with great fidelity, as must be the case if the symbols grounded in the sensory system are an accurate representation of the message encoded in the sequence of Braille cells in a text.

Solving the Interference Problem

One of the major factors that constrains the speed of Braille reading is the necessity of keeping the encoding process for each Braille cell distinct from its successor. The encodings cannot merge into one another or it would lead to interfering with the ability of the encoding process to result in the formation in the brain of separate and distinct neuronal groups for each letter in the sequence. In Braille reading, encoded representations of Braille cells are entering the brain at an average rate of 5 letters per second, or 300 letters per minute, or 18,000 letters per hour. For interference to be minimized, all four steps in the encoding process must be reset, or cleared, in less than 200 ms in order to be ready to encode the next Braille cell in the sequence.

This speaks to Deacon's comment that human language communication requires a "highly automated interpretation of symbolic relationships" (Deacon 1997). We believe that the four encoding steps we describe here fit the description of a highly automated system of encoding. The novice Braille reader, through an intense process of continuous presentation of the Braille cells to the finger pad, epigenetically develops the neuronal groups in the somatosensory system that encode for the alphabetic system encoded into the set of 26 Braille cells of Grade 1 Braille. Once this occurs the process of Braille reading becomes automatic. Each Braille cell in the sequence appears in the somatosensory system as a distinct encoded representation of a letter of the alphabet.

Spatiotemporal Entities

A remarkable feature of this automated system is that as the sequence of encoding steps unfolds, encoded entities appear and disappear with fluidity; the Braille code in action is ephemeral in this sense. It is here in the realm of spatiotemporal entities where structural patterns appear, endure for periods of time measured in milli-seconds, and then disappear.

We consider the finger pad *compression pattern* to be a spatiotemporal entity because of the compressions' extremely short duration, enabled by the pad's capacity to spring rapidly back to its original shape. The same is true for the compressed mechanoreceptors, which rapidly adapt after eliciting a brief burst of action potentials in sensory nerve fibers and are reset to pre-compression state. The spike trains pass along the sensory fibers in a series of electrochemical waves and as they pass each successive section of the nerve, the nerve rapidly returns to its pre-excited state. When the spike train reaches the brain, it travels through the previously established pathways to excite specific neuronal groups in the somatosensory system representing Braille cell morphology. The activated groups exist for approximately 100 ms and then they too disappear. Each one of the four steps involves the formation of spatiotemporal entities.

The term 'spatiotemporal' has been used by various authors to characterize brain activity. Varela et al., for example, wrote of "brain dynamics as coordinated spatiotemporal patterns" that involve synchronous neural network activation patterns that "emerge and disappear in waves that last 100–300 ms" (Varela et al. 2001). Sahin et al. found, in a study of linguistic activity in Broca's area in humans, distinct patterns of neuronal activity occurring in progressive steps of approximately 200 ms in duration composed of "fine-grained spatiotemporally patterned activity" (Sahin et al. 2009).

Also, in an animal study focused on uncovering what Nicolelis and Ribeiro referred to as the "neural code", they described finding "spatiotemporal firing patterns" of approximately 50 ms in duration involving neurons in the trigeminal somatosensory system that were correlated with subtle changes in tactile peripheral information (Nicolelis and Ribeiro 2006). It was concluded that, "monitoring large populations of neurons in sensory pathways has revealed...that information is encoded in the spatiotemporal activity patterns of entire neural ensembles" (ibid). In a previous paper in this journal we gave an extensive analysis of the Nicolelis and Ribeiro paper (Swan and Goldberg 2010b).

In each of the examples mentioned above the terms ‘spatiotemporal’ and ‘pattern’ are linked. Braille cells are characterized by the morphological patterns encoded in their structure. We have seen that pattern transfer is essential for the conversion of the morphology of Braille cells into neuronal groups in the somatosensory system of the brain.

Emergence

What is it that moves from the finger pad to the brain during Braille reading, and what is the substrate or medium through which it moves? One could argue that the entity that moves is a pattern. Obviously, the Braille cell itself does not enter the body. What does enter the body, however, is the encoded pattern of raised dots on the Braille cell. This pattern moves through various transformational encoding steps to arrive in the brain. In each one of these steps a new pattern is formed in a distinct substrate in such a way that the pattern encoded in the Braille cell is preserved.

The medium through which the pattern moves is composed of the differentiated, eukaryotic cells that form the tissues of the body and brain. Each of the cells is an entity that, in combination with millions of other cells, forms the cooperative ensembles that characterize complex multicellular organisms. Elsewhere we have discussed the essential role of molecular symbols in the intercellular communication among cells, including neurons, in multicellular organisms (Swan and Goldberg 2010a). If the encoded Braille cell is a symbol for a letter of the alphabet, and if the recognition of Braille cell patterns by the Braille reader is dependent upon the transfer of the information encoded in that pattern into the Braille reader’s brain, is that transfer accomplished utilizing molecular intercellular communication?

Intercellular communication is a necessary but not sufficient condition for such information transfer. We used Gould and Vrba (1982) term *exaptation* to characterize utilization of the pad, the mechanoreceptor grid, the sensory nerve fibers, and the interconnected web of somatosensory neurons, in the service of rapidly transferring signals arising from extremely small, minutely variable classes of environmental features such as Braille cells from the periphery to the brain. None of the structures involved in the transfers under discussion evolved for that purpose.

Epigenetic Flexibility

Consider the possibility of completely scrambling the Braille cell patterns so that, for example, a pattern that represented an ‘a’ in the old system would represent a ‘g’ in the new system. This would reflect a codemaker arbitrarily devising a completely new code for Braille. A Braille reader could readily learn, over time, to read using the new code. This capability demonstrates the flexible, nature of the code transfer system we have examined in Braille reading. It also emphasizes its epigenetic nature. Barbieri referred to the epigenetic representational system in the brain as the “secondary modeling system” (Barbieri 2010), and Edelman referred to it as the “secondary repertoire” (Edelman 1987). In both cases the secondary systems are distinguished from the genetic, primary systems, from which the secondary systems emerge. It is these secondary systems that are essential for the formation of neuronal

groups in the somatosensory systems of Braille readers that represent the Braille cell encoded letters of the alphabet. In this paper we have investigated the manner in which neuronal groups representing Braille cell morphology are formed in the somatosensory system of the human brain during Braille reading. This involves a process in which genetically evolved body and brain elements are recruited to support the emergent, epigenetic phenomenon of language-based, code-entity transfer from body to brain.

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