Evidence of behavioral recovery of somatic sensations following peripheral and central nervous system lesions challenges therapists to not only understand the nature and extent of the change, but the conditions under which the recovery can be maximized and the mechanisms underlying. This challenge requires input from basic sciences and rehabilitation fields. Integration of these fields will provide direction for the development and testing of scientific-based interventions designed to maximize recovery by driving and shaping neural reorganization.

The focus of this chapter will be on loss of somatic sensations, treatments currently available to address this problem, and the potential application of theories of perceptual learning and neural plasticity. More detail will be given to therapies following central nervous system (CNS) lesions, with particular reference to stroke. Comparisons will also be made in relation to loss following peripheral nervous system (PNS) lesions.

16.1 Nature of impairment and functional implications of loss

Definition and processing within the somatosensory system

Somatosensory function is the ability to interpret bodily sensation (Puce, 2003). Sensory systems are organized to receive, process and transmit information obtained from the periphery to the cerebral cortex. Within the somatosensory system submodalities of touch, proprioception, temperature sense, pain and itch are identified (Gardner and Martin, 2000). Detailed description of the system involved in sensory processing is provided in seminal texts such as Kandel, Schwartz and Jessell (Gardner and Martin, 2000). Further, neuroimaging studies are complementing and extending information gained from animal and lesion studies in humans (Schnitzler et al., 2000).

Two features of the structure and function of the system have particular implication for understanding the nature of impairment and neurorehabilitation. First is the high degree of specificity in the organization and processing of information. Specialized sensory receptors, modality-specific line of communication (Gardner and Martin, 2000), specific columnar organization and sub-modality-specific neurons in primary (SI) and secondary (SII) somatosensory areas (Mountcastle, 1997) support this specificity. Second, the opportunity for convergence of somatosensory information within the CNS (Mesulam, 1998), as well as the presence of distributed sensory networks and multiple somatotopic representation (Gardner and Kandel, 2000), impact on the scope for neural plastic changes and rehabilitation outcome.

Loss of somatic sensation following interruption to central and peripheral nervous systems

Loss of somatic sensations can be sustained due to damage at various levels of the sensory system, for example from receptors to peripheral nerves, spinal cord, brainstem and cerebral cortex. This may result from disease or trauma associated with a wide range of conditions (see Section E Disease-specific Neurorehabilitation Systems of Volume II). Somatosensory impairment may be in the form of anesthesia (total loss of one or more sensory submodalities in the region), hyposensitivity (reduced ability to
perceive sensations, including poor localization, discrimination and integration), or hypersensitivity (non-noxious stimuli become irritating, for example dyesthesia, paraesthesia or causalgia). Clinical description of loss should include identification of body part and submodalities affected as well as the level of processing impairment, for example detection, discrimination and integration of information across submodalities.

There are differences in the nature of the loss following peripheral and CNS lesions. For example, injury to the PNS involves well-defined loss of specific modalities that can be mapped relative to the nerve distribution or receptor location. In comparison, loss following CNS lesions such as stroke can result in very different patterns of deficit, from complete hemianesthesia of multiple modalities to dissociated loss of sub-modality specificity in a particular body location (see Carey, 1995 for review). Loss of discriminative sensibilities is most characteristic (Bassetti et al., 1993; Carey, 1995; Kim and Choi-Kwon, 1996), thresholds for primary sensory qualities (e.g., touch) are often indefinable (Head and Holmes, 1911–1912), qualitative alterations, response variability (Carey, 1995) and dissociated sensory loss (Roland, 1987; Bassetti et al., 1993) are observed, and hypersensitivity may be present initially or develop over time (Holmgren et al., 1990). Typically the loss is contralateral to the injury, although ipsilateral deficits are also reported (Carey, 1995; Kim and Choi-Kwon, 1996). The early and chronic pattern of deficit may be influenced by the site of lesion, relative sparing and redundancy within the distributed sensory system and neural plastic changes that may occur with recovery.

Functional implications of loss

Impairment of body sensations poses a significant loss in its own right and has a negative impact on effective exploration of the environment, personal safety, motor function, and quality of life (Rothwell et al., 1982; Carey, 1995). Everyday tasks such as searching for a coin in a pocket, feeling if a plate is clean when washing dishes, maintaining the grip of an object without crushing or dropping it, using cutlery, fastening buttons, writing and walking on uneven ground become difficult and often frustrating (Carey, 1995). The important role of sensation in motor function is particularly evident in: control of pinch grip (Johansson and Westling, 1984); ability to sustain and adapt appropriate force without vision (Jeannerod et al., 1984); object manipulation (Johansson, 1996); combining component parts of movement such as transport and grasp (Gentilucci et al., 1997); discrimination of surfaces at end of hand-held objects (Chan and Turvey, 1991); restraint of moving objects (Johansson et al., 1992); and adjustment to sensory conflict conditions such, as a rough surface (Wing et al., 1997). Moreover, the affected limb may not be used spontaneously, despite adequate movement abilities. This may contribute to a learned non-use of the limb and further deterioration of motor function after stroke (Dannenbaum and Dykes, 1988). These activity limitations impact on life roles, social communication, safety and participation in personal and domestic activities of daily living as well as sexual and leisure activities (Carey, 1995).

The personal and functional implications of sensory loss are highlighted in the words of a client who experienced sensory loss after stroke: "...my right side cannot discriminate rough, smooth, rigid or malleable, sharp or blunt, heavy or light. It cannot tell whether that which touches it as hand or tennis racket...it is frustratingly difficult to control or feel relaxed about any right-sided movement.... How does one trust a foot that "feels" as though it has no real connection with the earth? It is difficult to pick up or hold a pair of glasses or a sheet of paper when one's right hand/fingers feel uncontrollably strong and very big and clumsy, capable of crushing objects with one's grip yet incapable of letting go or throwing off even the lightest objects (e.g. a tissue).... better to feel something-however bizarre-than nothing."

Loss of somatic sensations also negatively impacts on rehabilitative and functional outcomes, as indicated in a review of stroke outcome studies (Carey, 1995). It has a cumulative impact on functional
deficits beyond severity of motor deficits alone (Patel et al., 2000) and negatively impacts on reacquisition of skilled movements of the upper limb (Kusoffsky et al., 1982; Jeannerod et al., 1984), postural control and ambulation (Reding and Potes, 1988). The importance of the sensory system as an early indicator of motor recovery after stroke has been suggested in neuroimaging (Weiller, 1998) and clinical (Kusoffsky et al., 1982) studies. It has been suggested that sensory reorganization may precede motor reorganization and may, in fact, trigger the latter (Weiller, 1998).

16.2 Assessment of somatic sensation

Guidelines for the selection of measures for use in clinical settings

The directive to follow evidence-based practice demands that clinicians employ quantitative measures that are valid and reliable. Numerous tests have been developed to evaluate the various qualities of sensibility, including touch, pressure, temperature, pain, proprioception and tactual object recognition (Carey, 1995; Dellon, 2000). In clinical settings we need information not only on thresholds of detection, but also on the ability to make accurate discriminations and recognize objects with multiple sensory attributes. Selection of suitable measures should be based on the following criteria: valid measurement of the sensory outcome of interest, for example discrimination; quantitative measurement; objectively defined stimuli; control for test bias and other clinical deficits; standardized protocol; adequate scale resolution to monitor change; good reliability and age-appropriate normative standards. For a critique of routine clinical and quantitative measures refer to Carey (1995), Dellon (2000) and Winward et al. (1999).

The need for standardized measures for use following stroke has been highlighted (Carey, 1995; Winward et al., 1999). Measures commonly used are largely subjective, lack standardized protocol (Lincoln et al., 1991; Carey, 1995); use gross scales such as “normal”, “impaired” or “absent” (Wade, 1992), have variable reliability (Winward et al., 1999), no defined criterion of abnormality, and are often insensitive or inaccurate (Carey et al., 2002c). Kim and Choi-Kwon found that discriminative sensation remained in only 3 of 25 stroke patients who were reported as having no sensory impairment on the basis of conventional sensory tests (Kim and Choi-Kwon, 1996).

Over the past decade new measures have been developed for use post-stroke. Clinical test batteries developed are the Nottingham Sensory Assessment (NSA) (Lincoln et al., 1991; Lincoln et al., 1998) and the Rivermead Assessment of Somatosensory Performance (RASP) (Winward et al., 2002). The RASP is standardized, uses seven quantifiable sub-tests of touch and proprioceptive discrimination and includes three new instruments, the neurometer, neurotemp and two-point neurodiscriminator. Intra and inter-rater reliability are high ($r = 0.92$). The NSA employs methods consistent with clinical practice, but are more detailed and standardized. Intra and inter-rater reliability are variable, with most tests showing relatively poor agreement across raters. The revised NSA reports acceptable ($k > 0.6$) agreement in only 12 of 86 items (Lincoln et al., 1998), and inter-rater reliability of 0.38–1.00 for the stereognosis component (Gaubert and Mockett, 2000).

New tests of specific sensory functions commonly impaired post-stroke have also been achieved. A test of sustained touch-pressure, based on the need to appreciate sustained contact of an object in the hand during daily manual tasks, was developed and impairment demonstrated in six patients with severe sensory deficit (Dannenbaum and Dykes, 1990). Empirical foundations for the test are required. New measures of tactile (Carey et al., 1997) and proprioceptive (Carey et al., 1996) discrimination provide quantitative measurement of the characteristic discriminative loss post-stroke. They are founded on strong neurophysiological and psychophysical evidence (Clark and Horch, 1986; Darian-Smith and Oke, 1980; Morley, 1980) and perception of the grid surfaces has been associated with cerebral activation in multiple somatosensory areas in unimpaired (Burton et al., 1997) and impaired (Carey et al., 2002a).
humans. The measures are quantitative, reliable, standardized, measure small changes in ability, have empirically demonstrated ability to differentiate impaired performance relative to normative standards (Carey et al., 1996, 1997) and advance current clinical assessment (Carey et al., 2002c). Tests of fabric discrimination and discrimination of finger and elbow position sense have also been developed (Carey, 1995) and are being empirically tested by us.

In addition to quantitative measures of sensibility, it is important to evaluate the presence and impact of the impairment in daily activities. This may involve structured interview and/or observation of occupational performance difficulties in tasks relevant to the patient. Focus of observations may include impact of loss on unilateral and bilateral tasks, level of independence, nature of difficulties (e.g., clumsy) and use of compensatory techniques. Tasks with varying sensory demands may be structured to systematically assess the impact of sensory loss. As yet there is no standardized test of the impact of sensory loss on daily activities.

16.3 Potential for recovery

The potential for recovery of somatosensory abilities has been demonstrated, following lesions to peripheral (Dellon, 2000) and central (Carey, 1995) nervous systems under both spontaneous and training-induced recovery conditions.

The natural history of recovery

The potential for recovery depends on regeneration of structures within the somatosensory system as well as the capacity for neural plasticity and reinterpretation of altered stimuli. These factors are further influenced by the level at which the system is interrupted, extent of injury, progression of disease, age, prior and intervening experience (Callahan, 1995; Carey, 1995; Dellon, 2000; see also Chapters 12, 13, and 27 of Volume II). Regeneration and recovery following damage to PNS has been relatively well described (Callahan, 1995; Dellon, 2000). In comparison, few studies have systematically investigated the natural history of spontaneous recovery of somatosensations post-stroke. Improvements have been reported across a range of measures including touch detection, texture and proprioceptive discrimination and object recognition (see Carey, 1995 for review). However, the extent of recovery is varied (Kusofsky et al., 1982), ranging from lasting deficits (Wadell et al., 1987) to “quite remarkable” improvement in capacities such as stereognosis (Schwartzman, 1972). The temporal aspects of recovery are also relatively unknown. Recovery appears most marked within the first 3 months (Newman, 1972), although ongoing recovery has been observed at 6 months and later (Kusofsky, 1990). It has been suggested that persistent deficit may be associated with particular lesion site (Corkin et al., 1970).

Evidence of training-induced recovery

Evidence of training-induced sensory improvements further highlights the potential for recovery following PNS (Dellon, 2000) and CNS (Carey, 1995) lesions. Moreover, improvements have been observed months and years post-injury, after the period of expected nerve regeneration (Dellon, 2000). Dellon (2000) asserts that results of sensory rehabilitation must be due to higher CNS functions and that cortical plasticity is the underlying mechanism. Similarly following stroke, task-specific and generalized training effects have been observed across tactile, proprioceptive and object recognition tasks, under quasi-experimental and controlled conditions (see Section Review of documented programs in relation to basic science and empirical foundations of documented of this chapter for review). In most instances the improvements have been observed after the period of expected spontaneous recovery. Neural plastic changes have also been proposed as the likely mechanism underlying these improvements.

Neural plastic changes associated with recovery of somatic sensations

Neural plastic changes occur in response to injury, but also as part of normal learning and development (refer
to Section A on Neural plasticity in Volume I). The cellular, physiological and behavioral mechanisms operating in adaptive brain plasticity are discussed in this section. Changes can occur immediately post-lesion or months and years later and can involve multiple levels of the somatosensory system (Jones and Pons, 1998). Longer-term stable changes, likely linked with change in synaptic connections and learning, are the most relevant for rehabilitation. Investigations in humans confirm reorganization in somatosensory regions following extensive use (Pascual-Leone and Torres, 1993), transient anesthesia (Rossini et al., 1994) and injury to the PNS (Merzenich and Jenkins, 1993) and CNS (Carey et al., 2002a; Wikström et al., 2000; see also Chapters 12, 13 and 27 of Volume II).

Studies of change in human brain activation, suggestive of neural reorganization, are providing new insights into the mechanisms underlying stroke recovery (Weiller, 1998; see also Chapter 5 of Volume II). Evolution of change over time and a potential relationship with recovery has been demonstrated in the motor system (e.g., Carey et al., 2005; Small et al., 2002; Ward et al., 2003). Findings indicate involvement of cortical and subcortical sites primarily within the pre-existing motor network and include recruitment of sites not typically used for the task and return to a more “normal” pattern of activation. Changes in SI (Rossini et al., 1998; Wikström et al., 2000), SII (Carey et al., 2002a) and thalamus (Ohara and Lenz, 2001) have been reported in the few studies of somatosensory recovery post-stroke. In serial pilot functional magnetic resonance imaging (fMRI) studies we found re-emergence of activation in ipsilesional SI and bilateral SII in a stroke patient who had marked sensory loss followed by good recovery (Fig. 16.1, Patient 1; Carey et al., 2002a). In comparison, only very limited recruitment in non-primary sensory areas was observed in the second patient who showed poor spontaneous recovery.

As yet little is known about neural mechanisms underlying functional recovery associated with specific training post-stroke in humans. Animal models highlight the benefit of experience in facilitating brain reorganization within motor and sensory systems. Controlled studies in primates suggest that both positive and negative patterns of brain reorganization can occur and that these can be “strongly influenced by appropriate rehabilitation programs after brain damage” (Nudo et al., 1996b; Nudo, 1999). Brain plasticity related to treatment-induced motor recovery has been suggested in the sensorimotor system of humans post-stroke (Lieberpt et al., 2000; Nelles et al., 2001; Carey J.R. et al., 2002). In addition, we have recently demonstrated good clinical recovery and changes in ipsilesional SI, bilateral SII and premotor areas following somatosensory training in a patient who showed poor spontaneous recovery in the 6 months prior (see Fig. 16.1, Patient 2). Investigation of changes in brain activation associated with training-induced recovery of somatosensations under randomized control conditions is now required.

16.4 Approaches to retraining impaired sensory function

Review of documented programs in relation to basic science and empirical foundations

Neurorehabilitation needs to be founded on a rigorous basic and clinical science platform and include cure in its mission (Seltzer, introduction to this text). Sensory re-education has been an integral part of the rehabilitation of patients with peripheral nerve disorders for many years. Some of the most influential programs are those developed by Wynn Parry and Salter (1976) and expanded by Dellon (1981; 2000). These programs employ principles of direct, repeated sensory practice, feedback through vision, subjective grading of stimuli such as texture and objects, verbalization of sensations and comparison of sensations experienced across hands. Evidence for the effectiveness of sensory training following peripheral lesions is reviewed in (Dellon, 2000, Chapter 11). Whilst some programs are directed to localized somatosensory deficits and regeneration of specific nerve fibers, Dellon (2000) highlights the need to focus on interpretation of altered stimuli at a cortical level based on evidence of neural plasticity.

There are a relatively limited number of documented sensory retraining programs designed for
use with stroke patients (Carey, 1995). Early studies suggesting improvement of sensory abilities (Vinograd et al., 1962; De Jersey, 1979) have lacked controls and a sound theoretical basis. The program by Vinograd et al. involved repeated exposure to test stimuli with 3D feedback from a box lined with mirrors while DeJersey used bombardment with multiple sensory stimuli. The only early study with a controlled design (Van Deusen Fox, 1964) also did not employ current theories of perceptual learning and neurophysiology and failed to obtain a therapeutic effect (see Carey, 1995 for review).

In comparison, Dannenbaum and Dykes (1988) described a therapeutic rationale based on neurophysiologic concepts and “rules governing somatosensory cortical reorganization after trauma”. Their program involved stimulation of “important sensory surfaces” at an intensity sufficient for appreciation and in a task that was motivating to the patient. Subjects were encouraged to attend to the input and given reinforcement. Electric stimulation and velcro were used in the early stages, followed by finger localization, exploration of velcro shapes and use of utensils taped with velcro. Improvement was reported in the case study presented.

Yekutiel and Guttman (1993) reported significant gains following sensory retraining in 20 stroke patients with chronic sensory impairment under...
controlled conditions. Principles of training were derived initially from peripheral nerve injury training programs (Wynn Parry and Salter, 1976), with contributions from psychology (Yekutiel, 2000). The essential principles included focus on the hand, attention and motivation, guided exploration of the tactics of perception and use of the “good” hand. The findings confirm that sensory discriminations are trainable after stroke and suggest a potential for generalized sensory gains. The authors reported variation in results across patients and noted that, “the method used – although aimed at higher brain centers – may still be too “peripheral” (Yekutiel and Guttman, 1993) (p. 243).

We have developed and investigated the effectiveness of two different approaches to training sensory discrimination: Stimulus Specific Training (SST) (Carey, 1993; Carey et al., 1993) and Stimulus Generalization Training (SGT) (Carey and Matyas, 2005). The programs employ principles derived from theories of perceptual learning (Gibson, 1991; Goldstone, 1998), recovery following brain damage (Bach-y-Rita, 1980; Weiller, 1998) and neurophysiology of somatosensory processing (Gardner and Kandel, 2000). SST was designed to maximize improvement in specific stimuli trained. It involves repeated presentation of targeted discrimination tasks; progression from easy to more difficult discriminations; attentive exploration of stimuli with vision occluded; use of anticipation trials; feedback on accuracy, method of exploration and salient features of the stimuli; and use of vision to facilitate calibration of sensory information (Carey, 1993; Carey et al., 1993). In comparison, the SGT approach was designed to facilitate transfer of training effects to untrained, novel stimuli and included additional principles of variation in stimulus and practice conditions, intermittent feedback and tuition of training principles (Carey and Matyas, 2005; Gibson, 1991; Schmidt and Lee, 1999).

SST effects were replicated in 37 of 41 time-series across 30 single-case experiments. Stimulus Generalization effects were found in 8 of 11 time-series across 11 subjects. Marked improvements, to within normal performance standards, were achieved within ten or fewer training sessions and maintained over follow-up periods of 3–5 months, suggesting a long-term therapeutic effect. SST effects were specific to the trained sensory perceptual dimension (tactile or proprioceptive) and stimulus type (e.g., texture gratings or fabrics). Generalized improvements in touch discrimination, that is untrained fabric surfaces, were achieved by the program deliberately oriented to enhance transfer (Carey and Matyas, 2005), as shown in Fig. 16.2. Meta-analysis of SST effects (tactile $z = -8.6, P < 0.0001$; proprioception $z = -4.3, P < 0.0001$) and SGT effects (tactile $z = -5.7; P < 0.0001$) supports the overall conclusion that tactile and proprioceptive discriminations are trainable following stroke and that both modes of training are effective. Finally, we have also applied the SGT approach to training friction discrimination and investigated its effect on the fundamental pinch grip task in pilot studies, with positive results (Carey et al., 2002b).

Two further retraining programs have been documented recently. These programs are in part derived from earlier programs, employ principles consistent with perceptual learning and neural plasticity and focus on training sensory and motor functions. Smania et al. (2003) describe a program of sensory and motor exercises for patients with pure sensory stroke. The program involved graded exercises, reported to be challenging for the patient, and feedback on accuracy and execution of task for each trial. Exercises focused on tactile discrimination using different textured surfaces, object recognition, joint position sense, weight discrimination, blindfolded motor tasks involving reach and grasp of different objects, as well as practice of seven daily life activities. Improvement in sensory and motor outcomes, as well as increased use of the affected arm in daily activities, was reported in the four cases studied.

Byl et al. (2003) described a program aimed to improve accuracy and speed in sensory discrimination and sensorimotor feedback. Principles, derived from studies of neural adaptation, included: matching tasks to ability of the subject, attention, repetition, feedback on performance and progression in difficulty. Sensory training focused on improving
sensory discriminations through games and fine motor activities, use of velcro on objects, retrieving objects from a box filled with rice and exercises in graphesthesia, localization, stereognosis and kines-thesia. Movements of the hand, mental rehearsal to reinforce learning and tasks to quiet the nervous system were also used. Patients were educated regarding the potential for improvement in neural processing and the unaffected hand was constrained through wearing of a glove. Training was investigated in 21 subjects with order of sensory or motor training crossed, although no placebo intervention period was employed. Improvements in sensory discrimination, fine motor function and musculoskeletal measurements of the upper limb were reported following sensory training. Gains were hemispheric and training specific.

In summary, recent training programs with successful outcomes have included a number of common principles consistent with theories of learning and neural plasticity. These include: attention to the sensory stimulus; repetitive stimulation with and without vision; use of tasks that are challenging and motivating; focus on the hand; graded progression of tasks and feedback on accuracy and execution. A more detailed discussion of principles of training related to perceptual learning and neural plasticity follows with suggestions for their application.

**16.5 Principles of neural plasticity and learning as they apply to rehabilitation of sensation**

**Identification and application of principles to optimize perceptual learning and brain adaptation**

Evidence of neural plasticity provides a strong foundation for restorative sensory retraining post-injury, both in acute and chronic phases. Review of theories of perceptual learning and the conditions under which neural plastic changes occur suggests a number of principles that have potential application in retraining somatosensations following PNS or CNS injury.
Most of the principles identified from these fields are complementary, consistent with the knowledge that neural plasticity underlies learning and recovery following injury. In addition, the physiology of processing somatosensory information must be considered in application to the sensory system. More recent sensory retraining approaches have begun to base their training on these principles (see Section Review of documented programs in relation to basic science and empirical foundations of this chapter for review). Key principles that have been successfully applied, or have potential for application, are discussed below. Their application is summarized in Table 16.1.

Neural plastic changes are experience-dependent (see Section A on Neural plasticity in Volume I; Nudo et al., 1996a) and the system is competitive (Merzenich and Jenkins, 1993; Weinreich and Armentrout, 1995). Functional reorganization has been demonstrated after behaviorally controlled tactile stimulation in intact animals (Recanzone et al., 1992). Forced use of the system, for example using constraint induced movement therapy, has also been associated with neural plastic changes in post-stroke motor recovery (Liepert et al., 2000). Even less intensive programs based on principles of motor learning found training-induced changes (Carey J.R. et al., 2002). Importantly, repetitive use alone may not be sufficient to effect changes in cortical representation. Rather changes are associated with specific skill learning, consistent with a

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<td>of specific stimuli</td>
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<td>Attentional exploration</td>
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Table 16.1. Summary of principles of sensory training derived from theories of perceptual learning, neural plasticity and physiology of the somatosensory system.
“learning-dependent” hypothesis of neural plasticity (Karni et al., 1995; Plautz et al., 2000). Sensory neurorehabilitation should therefore challenge the sensory system using repeated stimulation of targeted sensory tasks coupled with an intensive perceptual-learning based training program.

Learning is reported to be maximal for the specific task trained (Gibson, 1969; Goldstone, 1998; Sathian and Zangaladze, 1997), consistent with highly specific organization of the system (see Section Definition and processing within the somatosensory system of this chapter for review) and evidence that functional reorganization is directly linked with changes in cortical regions engaged by these inputs (Recanzone et al., 1992). Repetition over time with an increasing number of coincident events serves to strengthen synaptic connections (Byl and Merzenich, 2000). However, competition between afferent inputs for connections in the sensory cortex (Merzenich and Jenkins, 1993) suggests the need for caution with overstimulation of a specific site at the expense of related areas. Consequently to maximize task-specific learning, training stimuli and the method of processing the information should match targeted discrimination tasks (Carey et al., 1993). Training of important sites normally responsible for the sensation, for example the hand (Dannenbaum and Dykes, 1988; Yekutieli and Guttman, 1993), and discriminations characteristically impaired and important for daily function (Carey et al., 1993) have been recommended.

Motivation is important in learning (Goldstone, 1998) and recovery after brain injury (Bach-y-Rita, 1980), and the brain responds to meaningful goals (Nudo et al., 1996b). Training should therefore be goal directed, interesting and demanding if it is to tap into the brain’s potential for functional reorganization (Byl and Merzenich, 2000; Yekutieli, 2000). It should provide regular opportunities for success, with reinforcement to encourage motivation and participation (Carey, 1993; Yekutieli, 2000).

Attention is crucial in perceptual learning. Attentive exploration of stimuli allows purposeful feedback within the sensory-perceptual system (Epstein et al., 1989) and perception becomes adapted to tasks by increasing the attention paid to important features (with less noticing of irrelevancies) (Gibson, 1969; Goldstone, 1998). Perceptual learning (Goldstone, 1998) and neurophysiological (Johnson and Hsiao, 1992) evidence propose that “distinctive features of difference” are learned and form the basis of transfer of training. Attention is also important in the modulation of cortical plasticity (see Chapter 11 of Volume II), particularly in early stages of plastic changes and learning (Karni et al., 1995). Thus patients should actively (where possible) and purposively explore sensory stimuli with attention directed to distinctive features of difference. This may be facilitated through requiring a response and guiding the patient to search for distinctive features (Carey et al., 1993). Further, as vision may dominate tactile and proprioceptive senses in some instances (Clark and Horch, 1986; Lederman et al., 1986), exploration of stimuli with vision occluded should be included to allow subjects to focus specifically on the somatic sensations (Carey et al., 1993).

Anticipation may facilitate recruitment of existing or new sensory sites in the brain. Similar brain sites are active under direct stimulation and anticipated stimulation conditions (Roland, 1981). Further, prior and subjective experience can influence early stages of information processing and facilitate stimulus differentiation (Goldstone, 1998). Anticipation trials, in which the patient is informed that a limited set of previously experienced stimuli will be used (Carey et al., 1993), may tap into this capacity and encourage new neural connections. A patient may also be encouraged to imagine what a stimulus should feel like, based on evidence that haptic (tactile and proprioceptive) information is represented through imagery (Klatzky et al., 1991).

Augmented feedback on accuracy of response outcome and on performance is important in skill acquisition (Schmidt and Lee, 1999) and may enhance perceptual learning (Gibson, 1969). Although improvement in perceptual discriminations may be experienced in unimpaired subjects without extrinsic feedback in some cases (Epstein et al., 1989), practice with correction can enhance learning.
We found that repeated exposure alone was insufficient to effect a positive training outcome in the majority of cases post-stroke (Carey et al., 1993; Carey and Matyas, 2005). Thus feedback on accuracy of response and performance, for example method of exploration (Lederman and Klatzky, 1993), should be provided. Feedback should be immediate, precise and quantitative to maximize acquisition (Salmoni et al., 1984). Summary feedback also enhances learning (Salmoni et al., 1984) and should be provided at the end of each training session.

Calibration of perceptions would also appear to be important. This may involve comparison of the sensation with the other hand (Gibson, 1969) and use of vision to facilitate cross-modal calibration (Lederman et al., 1986), consistent with activity in visual cortical regions during tactile perception (Zangaladze et al., 1999). Computational neural models indicate that when two modalities are trained at the same time and provide feedback for each other, a higher level of performance is possible than if they remained independent (Becker, 1996). Moreover, cross-modal plasticity in sensory systems (see Chapter 10 of Volume II) may facilitate alternate and new neural connections.

Finer perceptual differences are able to be distinguished through exposure to a series of graded stimuli (Ahissar and Hochstein, 1997; Goldstone, 1998). Graded progression facilitates perceptual differentiation, especially of complex stimuli, as presentation of an easy discrimination first allows the subject to allocate attention to the relevant dimension (Goldstone, 1998). Further, transfer from one stimulus to another within a unidimensional sensory quality requires presentation in a graded manner (Gibson, 1969). Thus training should progress from easy to more difficult discriminations across stimuli and within a unidimensional sensory quality.

Performance is better on frequently presented items than rare items (Allen and Brooks, 1991). In addition, best available evidence suggests that training should continue for some time after “mastery” to increase retention (Lane, 1987). This further suggests the need for repetition and intensive training.

**Specificity of learning and principles to facilitate learning transfer**

Whilst the above principles have been associated with positive perceptual learning, there are limits on the generality of perceptual learning. Perceptual learning is usually highly specific to the task, receptor location and method of processing (Sathian and Zangaladze, 1997; Goldstone, 1998). Similarly, we found highly specific training effects in tasks employing the same sensory dimension (tactile or proprioceptive), sub-modality (grid or fabric textures) and body location (fingertip or wrist) with SST post-stroke (Carey et al., 1993; Carey and Matyas, 2005). However, perceptual transfer is possible in some instances with unimpaired subjects (Epstein et al., 1989; Ettlinger and Wilson, 1990; Spengler et al., 1997). Similarity between original and transfer tasks is an important factor influencing the degree of transfer (Gibson, 1969). It has been suggested that transfer should be more prominent where the stimuli are more complex and potentially share a number of distinctive features (Gibson, 1991; Goldstone, 1998). Transfer across body sites has also been reported in unimpaired systems (Sathian and Zangaladze, 1997; Spengler et al., 1997), and may be influenced by the attention demands and complexity of the task (Ahissar and Hochstein, 1997).

Principles of learning that facilitate transfer of training effects in unimpaired subjects have potential application following injury. Transfer of training effects is more effective when variation in stimuli is employed (Gibson, 1991; Goldstone, 1998; Schmidt and Lee, 1999). Optimally this should include training across a variety of stimuli with a wide range of distinctive features, for example roughness characteristics, as well as variation in tasks and environments (Carey and Matyas, 2005). To achieve grading, progressive difficulty should be defined across stimuli sets as well as within sets (Carey and Matyas, 2005).

Intermittent feedback on accuracy of response (Winstein and Schmidt, 1990) and specific instruction on principles of training and how these apply
across tasks (Cormier and Hagman, 1987) have also been associated with enhanced transfer and retention. Further, an important part of learning transfer tasks is acquiring the capacity to cope with novel situations (Schmidt and Lee, 1999). This suggests the need to provide exposure to novel stimuli with opportunity to get feedback on the act of generalization (Carey and Matyas, 2005).

In summary, positive findings from studies of sensory retraining (see section Review of documented programs in relation to basic science and empirical foundations of this chapter for review) support the application of principles of training derived from literature on perceptual learning and neural plasticity. Further, the nature of training, that is stimulus specific versus generalization optimized, appears crucial to outcome. Evidence of a learning phenomenon associated with sensory retraining post-stroke has been quantified in the intervention time-series data of our patients (Carey, 1993; see also Fig. 16.2). The improvement curve was consistent with that described in the learning literature (Lane, 1987; Epstein et al., 1989) and in studies of neural plasticity (Recanzone et al., 1992). However, in contrast to unimpaired subjects (Epstein et al., 1989), the characteristic learning curve was only achieved under supervised training conditions (Carey et al., 1993). The potential for generalization of training within a sensory dimension has also been demonstrated post-stroke, provided a program designed to enhance transfer is used (Carey and Matyas, 2005). Other programs that have employed training across a variety of tasks have also found generalized training effects (Byl et al., 2003; Smania et al., 2003; Yekutiel and Guttman, 1993).

16.6 Future directions for the integration of basic science in clinical practice, as applied to neurorehabilitation of somatic sensation

Brain networks may reorganize to optimize stroke recovery. However, despite evidence of behavioral improvement, it is not known to what extent training-induced recovery is associated with changes in the functional neuroanatomy of sensation in humans. In particular it is unknown whether sites different to those typically used are involved in the recovery process, possibly suggestive of different behavioral strategies. Clinically effective sensory training programs, derived from theories of perceptual learning and recovery following brain damage, may be used to test for outcomes related to brain adaptation. Confirmation of the prediction that neural plastic changes occur primarily within the pre-existing somatosensory system (Weinreich and Armentrout, 1995), will highlight the importance of sparing and dynamic adaptation within pre-existing sensory sites. Evidence of recruitment of different sites may identify involvement of other systems important in recovery, such as attention (see Chapter 11 of Volume II) and visual (see Chapter 10 of Volume II) systems. This will advance our understanding of whether training is operating at a level of restitution or substitution within the system and provide insight into behavioral strategies associated with training. Comparison with motor recovery findings will help determine if there is a common model of neural plasticity associated with motor and somatosensory recovery.

Systematic investigation of the conditions under which behavioral improvement and neural repair is most effectively achieved is required to provide ongoing direction for the development of science-based interventions. For example, the timing (post-injury) and intensity of training requires investigation, given evidence of possible maladaptive changes (Merzenich and Jenkins, 1993; Nudo et al., 1996b). Investigation of the need for specific training, compared to non-specific exposure, and the neural outcomes of learning transfer (Spengler et al., 1997) will help elucidate the mechanisms and brain regions involved in different training methods. Similarly, different principles of training (e.g., cross-modality matching and feedback on accuracy) require systematic investigation of their contribution as they may involve different neural structures and mechanisms. Paradigms that permit investigation of component stages in neural processing need to be conducted and interpreted.
using models of analysis that focus on connectivity within the system.

Knowledge of the relationship between brain activation and recovery will have predictive significance in relation to identifying patients who are likely to show spontaneous recovery and/or who are able to benefit from training. Potential explanations for individual differences in the nature and extent of recovery may relate to lesion site (Zemke et al., 2003) and remote changes in structure, including diaschisis (Seitz et al., 1999). Investigation of the association between structural brain changes and the brain's capacity for reorganization is indicated.

Further development of current training programs is also indicated. Programs reviewed (see Section Review of documented programs in relation to basic science and empirical foundations of this chapter for review) have incorporated principles consistent with perceptual learning and neural plasticity. However, individual features of the training protocols have not been dissected. This is necessary to identify the critically important elements associated with successful learning and transfer. Previous studies have provided some insight into the boundaries of spontaneous and facilitated transfer with stroke patients (Carey et al., 1993; Carey and Matyas, 2005). Investigation of similarity of trained and transfer tasks, method of information processing, level of task difficulty and relative body location on learning transfer is needed to guide clinical training programs and clarify the nature of what is being learnt.

The most optimal combination of principles may also vary with individual patient characteristics including the nature of loss (e.g., detection versus discrimination versus multisensory integration), the phase of recovery (acute versus chronic) and the site of lesion (PNS versus CNS or specific location within these). Systematic investigation of these is indicated. The focus of training could also be expanded to include training in discrimination of size, shape and weight of objects, detection of slip when holding objects, regulation of pressure during grasp and spontaneous use of the limb. Finally, the ability to modify sensory abilities experimentally opens up an experimental paradigm for future investigations of the relationship between sensation and other abilities, such as pinch grip, and the effect of improving sensation on motor function and activities of daily living.

Acknowledgements

I wish to acknowledge the contribution of collaborators who have worked with me on various aspects of research related to sensory recovery and retraining following stroke. In particular Ass/Prof Thomas Matyas and Ms Lin Oke have collaborated on the clinical studies investigating methods of assessing and training somatosensations post-stroke. Ongoing clinical studies are being conducted also in collaboration with Prof Derek Wade and Dr Richard Macdonnell. Investigation of neural outcomes associated with motor and sensory recovery under spontaneous and training-induced recovery conditions is being conducted in collaboration with a number of researchers including Prof Geoffrey Donnan, Dr David Abbott, Dr Gary Egan, Prof Aina Puce and Prof Rüdiger Seitz.

REFERENCES

and motor rehabilitation of the upper limb following the principles of neuroplasticity: patients stable poststroke. *Neurorehabil Neural Re* 17, 176–191.


Plautz, E.I., Milliken, G.W. and Nudo, R.J. (2000). Effects of repetitive motor training on movement representations in...


