Training of Somatosensory Discrimination After Stroke
Facilitation of Stimulus Generalization

ABSTRACT

Objective: Task-specific learning typifies perceptual training but limits rehabilitation of sensory deficit after stroke. We therefore investigated spontaneous and procedurally facilitated transfer of training effects within the somatosensory domain after stroke.

Design: Ten single-case, multiple-baseline experiments were conducted with stroke participants who had impaired discrimination of touch or limb-position sense. Each experiment comprised three phases: baseline, stimulus-specific training of the primary discrimination stimulus, and either stimulus-specific training of the transfer stimulus or stimulus-generalization training. Both the trained and transfer stimuli were monitored throughout using quantitative, norm-referenced measures. Data were analyzed using individual time-series analysis and meta-analysis of intervention effects across case experiments.

Results: Stimulus-specific training was successful for trained texture and proprioceptive discriminations, but it failed to show spontaneous transfer to related untrained stimuli in the same modality in seven of eight experiments in which this was possible. In contrast, intramodality transfer was obtained with stimulus-generalization training in four of five experiments that investigated stimulus-generalization training of texture discrimination. Findings were confirmed by meta-analysis.

Conclusions: Our findings demonstrate generalization of training within a somatosensory modality poststroke, provided that a program designed to enhance transfer is used. This has implications for the design of efficient rehabilitation programs.

Key Words: Sensation, Rehabilitation, Cerebrovascular Accident, Transfer of Training
Generalization of intervention effects to untrained tasks is central to sensorimotor neurorehabilitation. Task-specific training, although effective, has the potential to be very costly, and novel tasks will present continuing problems. Discovery of effective training methods also able to achieve transfer of gains to novel tasks is thus essential. Furthermore, investigation of the boundaries of transfer is increasingly regarded as a key ingredient to a proper understanding of learning effects in the sensorimotor system. In the sensory domain, investigation of stimulus-generalization effects could help clarify what is encoded about the stimuli during the training experience.

“Generalization of training” or “transfer of learning” to an unpracticed task has been investigated with healthy subjects in various domains, including perception. Empirical investigations in the perceptual learning literature suggest that transfer is possible in some instances. However, discrimination training is often highly specific to the task. A general finding is that similarity between the trained and transfer tasks is an important determinant of positive transfer. The dimensions of similarity that seem to matter include whether the novel transfer task is within the same perceptual dimension as the trained task, the similarity of the required response, and the similarity in method of processing the information. Body location, density of receptors, and organization of the somatosensory cortex may also affect transfer of learning in somatosensory discrimination. The training conditions under which transfer might be expected also need to be considered. Principles that may enhance transfer of training have been identified in the motor-learning literature. However, exposure and feedback may be adequate for perceptual transfer, at least for unimpaired subjects.

Generalization of training within the same perceptual dimension or sensory modality has received only limited investigation in stroke patients. Spontaneous improvement in related visual functions was found in a controlled study that trained a single visual function of patients with cerebral blindness. In contrast, we found stimulus-specific training (SST) effects across tactile and proprioceptive discrimination tasks poststroke. Studies that have trained multiple modalities simultaneously, used objects with multisensory demands, or employed sensorimotor tasks have reported improvement in untrained sensory tasks, suggesting the potential for generalized somatosensory effects. These results are consistent with findings of spontaneous transfer across multidimensional tasks in healthy subjects. Although spontaneous transfer may be achieved by unimpaired subjects when tasks and processing activities are highly similar, it is unknown whether these conditions are adequate for individuals in whom the perceptual system is damaged. Furthermore, the potential for transfer of training under different training conditions has not been systematically investigated within the somatosensory domain after stroke.

We have focused our research on rehabilitation of somatosensory deficits, particularly touch and proprioceptive discrimination. These deficits are characteristic of the loss experienced and are reported in approximately 50% of stroke patients. Such deficits pose substantial difficulties in reception of sensory information and exploration of the environment and have detrimental effects on spontaneous use of hands, object manipulation, and precision grip. Moreover, sensory loss has a negative effect on personal safety, functional outcome, and quality of life, and it influences length of stay in the hospital (see Carey for review), highlighting the functional importance of training these capacities.

This investigation of generalization effects followed our initial findings that stroke-induced impairments of texture discrimination and limb-position senses are trainable. Improvements were specific to the stimuli trained and confirmed the expected independence of tactile and proprioceptive performance. Although lack of transfer across tactile and proprioceptive discrimination was expected, those data do not address transfer across stimuli of the same type, such as textures with different distinctive features of roughness. Efficient retraining of somatosensory discrimination abilities requires an understanding of the similarity required to achieve successful transfer.

We therefore conducted a series of ten controlled, multiple-baseline, single-case experiments to investigate transfer across stimuli within the same sensory-perceptual dimension using either SST or stimulus-generalization training (SGT). The design permitted training the primary discrimination stimuli while simultaneously monitoring the influence of this treatment on the transfer stimuli, and the design delayed introduction of generalization-enhanced training to after this control phase. Study 1 investigated spontaneous transfer of training effects within tactile and proprioceptive domains after SST. Study 2 investigated transfer to novel stimuli within the tactile dimension using a program modified to facilitate SGT.

Transfer tasks were selected to require the same sensory-perceptual dimension and body location as the trained task, as these features of similarity seem to be important in perceptual learning. Tactile stimuli were two types of textured surfaces: plastic grids and fabrics. These stimuli
require processing within the same tactile domain and are both explored with the fingertip but have different surface characteristics. The proprioception tasks involved discrimination of imposed wrist positions in the flexion-extension and ulnar-radial deviation planes of movement. They required the same type of limb-position discrimination and the same body location (i.e., the wrist), but they used positions within different planes of movement. Norm-referenced, quantitative, and reliable measures of these tactile and proprioceptive discriminations were available as outcome measures.\textsuperscript{12,14,15}

**MATERIALS AND METHODS**

**Study 1: Spontaneous Transfer of Training Effects with SST**

**Subjects**

Five stroke patients with tactile or proprioceptive discrimination impairment, as tested by the measures described below, were studied. They were medically stable, had adequate comprehension of instructions for assessment, had no peripheral neuropathy or previous central nervous system dysfunction, and were free of unilateral spatial neglect based on clinical observation and standard neuropsychological tests. Patients meeting these criteria were selected sequentially, as they presented, and gave voluntary informed consent. The project was approved by the human ethics committees of LaTrobe University and participating hospitals and conformed to the Helsinki Declaration.

**Materials**

Measures of touch discrimination were the Tactile Discrimination Test (TDT)\textsuperscript{15} and the Fabric Matching Test (FMT).\textsuperscript{12} The TDT employed finely graded plastic surfaces marked by ridges at set spatial intervals. Texture grids were presented in sets of three, with two surfaces identical and one different. The FMT comprised two identical sets of ten cotton-based fabrics, ranked from smooth to rough by unimpaired subjects. These measures have high retest reliability and good discriminative validity and normative standards have also been established for these tests.\textsuperscript{14,16}

**Procedure**

Five single-case experiments were conducted to investigate spontaneous transfer of training to related stimuli in study 1. Two experiments investigated transfer within the tactile-discrimination dimension and three within proprioception. In the tactile experiments, texture grids were employed as the primary stimuli to be trained and the fabrics as the transfer stimuli. Imposed wrist positions within the flexion-extension plane were the primary trained proprioception stimuli and positions within the ulnar-radial deviation plane the transfer stimuli.

The typical case experiment had three phases, each phase comprising ten sessions in which both the trained and transfer tasks were assessed. Assessment sessions were scheduled 48–72 hrs apart. In the first phase, both tasks were monitored only. In the second phase, the texture grid or flexion-extension stimuli were trained over ten treatment sessions, interspersed between assessment sessions, while baseline monitoring continued on the transfer response. In the third phase, treatment was introduced for the transfer stimuli over ten sessions. This permitted investigation of the subject’s potential for a SST effect on the transfer task. Follow-up was conducted after an interval equivalent to the combined time of baseline and intervention phases (i.e., 12–14 wks after the end of training).

**Test Procedure and Scoring**

The TDT was administered after standard instructions were given.\textsuperscript{15} Subjects tactually explored each set of comparison surfaces with their preferred finger and indicated the odd texture in a three-alternative, forced-choice design. Five different triplets, spanning Weber ratios of 0.033–1.0, were each presented ten times in random order to obtain the discrimination limen. The limen was derived from fitting a cumulative normal distribution to the probabilities of correct responses. In the FMT, subjects attempted to tactually match each of the ten test surfaces with identical comparison surfaces.\textsuperscript{12} Fabrics were presented behind a curtain, using a predetermined random order and a standard set of instructions. The preferred finger used in the TDT was also used for the fabric test. Response and target rank orders were correlated with Spearman’s rho to quantify fabric discrimination ability. Rho values were transformed with Fisher’s $z$, and the scale was inverted by subtracting scores from the allocated maximum value of 3.5 $z$ score to make graphical presentation of ther-
aptic change consistent in direction with TDT scores.

In the WPST for flexion-extension and ulnar-radial deviation, the examiner moved the subject's hand, via a lever, to 20 different predetermined wrist positions. Average absolute error between actual and response positions was then calculated as the index of limb position sense for each test.

**SST**

The SST program was designed to maximize improvement of the specific sensory discriminations trained.\(^8,16\) Principles of training included: repeated presentation of targeted discrimination tasks (as learning is reported to be maximal for the specific task trained); progression from easy to more difficult discriminations; attentive exploration of stimuli with vision occluded; use of anticipation trials; feedback on salient sensory features of the stimuli, accuracy of judgments, and method of exploration; comparison of the sensation with the other hand; use of vision to facilitate intermodal calibration of sensory information; summary feedback; and intensive training.\(^8,16\) These principles were applied to training each stimulus, as described below.

In the SST program, training tasks were the same as the assessment tasks, but typically used a restricted range and number of stimuli. Five sets of grids, with differences in surfaces ranging from 3.3% spatial increase to 100% spatial increase, were used for training texture grids, as previously described.\(^8\) Subjects explored each set of comparison grid surfaces with their preferred finger and indicated the odd texture. Training of fabric discrimination used the fabrics of the FMT. Subjects were required to match comparison surfaces to a restricted range of target surfaces and, in some trials, to identify which fabrics they had touched. Training employing a subset of fabrics with four levels of difference, from large to small differences, provided a framework to assist interpretation of the relative smoothness and roughness of the set of surfaces. To train for flexion-extension position sense,\(^8\) the subject’s wrist was moved to a position in the flexion-extension range. Subjects then indicated perceived position of the wrist from a set of defined angles. Seven positions were used to achieve four levels of stimulus difference (i.e., 90-, 60-, 30-, and 15-degree differences). In training for ulnar-radial position sense, six positions were used to achieve four levels of stimulus difference (i.e., 40-, 25-, 15-, and 7-degree differences).

Subjects were initially presented with the largest stimulus differences for which <100% accuracy had been shown in testing during the baseline phase. Stimulus sets were explored with vision occluded, and subjects gave a response in an attempt to encourage attention to stimulus differences. Quantitative feedback on accuracy of judgments was provided by allowing subjects to visually check the defined differences (cross-modality calibration) and by comparing the sensory experience using the affected and other hand (within-modality calibration). Salient sensory features of stimuli (e.g., roughness characteristics of contour, spatial density) were highlighted by the trainer, and irrelevant variation de-emphasized, in an attempt to sensitize subjects to the distinctive features of difference. Qualitative feedback on how subjects explored the stimuli (e.g., use of lateral movement of the fingertip over the surfaces or imagining a reference point of where the hand was pointing in the proprioception task) was also given. After initial exposure to stimuli of a particular stimulus difference level, a series of anticipation trials were conducted in which subjects were instructed that the same stimuli set previously explored would be presented. Thus, choices were limited and subjects could make judgments with knowledge of what to expect to feel. Subjects responded whether the stimuli were the same or different and identified which of the limited stimuli was felt. Feedback on accuracy, sensation, and method of exploration was provided, as above. When correct discriminations occurred in at least three of four consecutive occasions, the next finer stimulus difference was introduced. Summary feedback on the individual’s accuracy of judgments and method of exploration was also provided at the end of each training session. Training was intensive, with sessions lasting 40–60 mins, three times a week.

**Data Analysis**

First, each single-case experiment was analyzed separately for stimulus-specific and generalized training effects. Second, these results were combined in a meta-analysis to obtain an overall conclusion.

Time-series data were analyzed using visual (graphical) and statistical analyses.\(^8,13\) For graphical analyses, standard single-case charts were evaluated visually by the authors and a panel of three trained, independent analysts who were naïve to the purpose of the study. The analysts’ type I error (false alarms) and type II error (missed treatment effect) rates were calibrated using computer-generated charts in which null or non-null effects were presented unidentified and in random order.\(^8,16\) Analysts were required to make separate judgments of systematic change between phases according to defined criteria.

Statistical interrupted time-series analyses (ITSA)\(^13\) were also conducted for each single-case experiment. The initial step comprised model identification, in which three curvilinear models of
learning likely to adequately describe the intervention effect were compared for goodness of fit using the curvilinear regression routines of SPSS. The models \( Y = a + bx \), \( Y = ax^b \) and \( Y = ae^{bx} \) were compared, consistent with earlier investigations. Residuals from the models were examined by autocorrelation and partial autocorrelation methods to detect remaining serial dependence in the data. The best-fitting model with residuals free of positive serial dependence was selected to describe the data and perform ITSA. After investigation and deletion of outliers, ITSA were tested for trend and level effects between phases to evaluate intervention effects, as previously described. A systematic difference between phases was judged to be present if either a statistically significant trend or level effect was present. Determination of a spontaneous transfer effect involved (a) identification of an intervention effect on the primary trained response together with (b) identification of a simultaneous, systematic change in a therapeutic direction in the transfer response.

Finally, meta-analyses were conducted to complement individual subject ITSAs and assist a generalized conclusion across the case experiments. The type I error probabilities of each ITSA were converted to \( z \) scores and then averaged to obtain a pooled estimate. Separate meta-analyses examined stimulus-specific intervention effects, spontaneous generalization effects, and the effect of the intervention designed to facilitate generalized improvement in texture discrimination.

**Study 2: Transfer of Training Across Textured Surfaces Using a Program Designed to Facilitate Generalization to Novel Stimuli**

**Subjects**

Five further stroke patients, who met selection criteria previously described and had tactile discrimination impairment, were investigated. Patients meeting these criteria were selected sequentially, as they presented, and gave voluntary informed consent.

**Materials**

The FMT was again employed, as previously described. The Grid Matching Test (GMT)\(^1\) tested stimulus-matching ability. The test used the same finely graded plastic grids as for the TDT but employed a stimulus-matching procedure, as in the FMT. Sixteen surfaces, with spatial intervals ranging from 1500 to 3000 \( \mu \)m, were placed on test and comparison texture wheels and presented for tactual exploration through openings in the test apparatus. Reliability, discriminative validity, and normative data have been obtained for this test.\(^1\)

**Procedure**

This study comprised five multiple-baseline, single-case experiments. Performance on the GMT and FMT was monitored throughout the time series. The first phase comprised baseline only. In the second phase, SST (described in study 1) was introduced for texture grids while the transfer response was monitored. In the third phase, SGT was introduced while monitoring of the untrained transfer response continued. Follow-up was conducted 12–14 wks after the end of training.

**Test Procedure and Scoring**

The stimulus-matching procedure was used for both tests. For the GMT, the subject was required to tactually match each of eight test surfaces (selected from the set of 16) against the identical set, with vision occluded. For the FMT, subjects were required to match each of the ten test surfaces with the ten comparison surfaces. Testing took approximately 10–15 mins for each test. Stimulus-matching ability was quantified by correlating the response and test values with Pearson’s \( r \) (GMT) and Spearman’s \( \rho \) (FMT). Correlation coefficients were then normalized with Fisher’s \( z \) transform. A higher score reflects better matching.

**SGT**

The SGT program was designed to facilitate transfer of training effects to untrained, novel stimuli. To achieve this, the additional principles of variation in stimulus and practice conditions, intermittent feedback, and tuition of training principles\(^1,2,19\) were included, as these have been associated with enhanced transfer and retention. A variety of training surfaces (e.g., paper, glass, leather, and rubber, but not fabrics) were employed in the SGT program. The surfaces comprised a range of distinctive features of roughness, including contour, surface pattern, and grit. Each different type of surface was graded from smooth to rough across five stimuli and included small to large differences. First, large differences were introduced across a subset of surface types, followed by medium and fine differences. Thus, progressive grading of difficulty was across stimuli and within stimuli, and subjects had the opportunity of making similar discriminations across novel surface types. Feedback on salient sensory features, accuracy, and exploration method (as for SST) was given intermittently rather than at every trial, and subjects were encouraged to check the accuracy of their own performance. Feedback was also given on the transfer task of identifying new distinctive features of roughness in novel stimuli. Specific tuition on principles underlying training, such as use...
of anticipation trials and feedback, and how these apply across tasks that the client may encounter in other environments were also included. Repeated presentation of stimuli, attentive exploration with vision occluded, anticipation trials, summary feedback, and intensive training were also incorporated, as for SST.

Data Analysis

Case charts were analyzed visually and statistically for trend and level effects. Individual time series were graphed for visual analysis, and statistical analysis was conducted, after model identification, as previously described.

RESULTS

Study 1

Background data of subjects is detailed in Table 1. All subjects showed marked impairment on the TDT (i.e., unable to consistently discriminate the largest texture difference of 100% spatial increase [criterion of normality, <37.7% spatial increase\(^\text{\textsuperscript{15}}\)]. Impaired performance was also evident across multiple modalities, using the following tests and normative standards: wrist proprioception using the WPST for flexion-extension (criterion of normality <9.5 degrees\(^\text{\textsuperscript{14,16}}\)); pressure discrimination using Semmes-Weinstein monofilaments (normal threshold = 0.02–0.13 filament\(^\text{\textsuperscript{20}}\)); hot/cold discrimination using the Roylan hot and cold discrimination kit (A629-1) (age-matched, healthy controls detect at least 9 out of 10 correct\(^\text{\textsuperscript{19}}\)).

Model Identification

The logarithmic model \( Y = a + b \ln X \) accounted for most variance in the intervention data for eight of the ten time series, without high positive autocorrelation in the residuals of any series. Statistically significant negative autocorrelation (lag 2) was identified only in two baseline phases. The analysis of residuals thus confirmed selection of a logarithmic model for ITSA.

Intervention Effects in the Trained Response

Intervention effects were clearly apparent in three of the five first-trained primary responses after SST (Fig. 1, S01 to S03). These improvements were detected above any changes between the first and second phase of baseline of the second discrimination response. Improvements were marked and immediate, with changes in performance noted after the first training session. Performance scores achieved by the end of training were within the normal range\(^\text{\textsuperscript{15}}\) and similar to those of the other hand in all three cases. The panel of judges unanimously detected a systematic change (\( P \sim 0.00 \)) in all three series and did not identify a significant

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**TABLE 1** Background information of subjects in study 1

<table>
<thead>
<tr>
<th>Subject</th>
<th>S01</th>
<th>S02</th>
<th>S03</th>
<th>S04</th>
<th>S05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yrs</td>
<td>44</td>
<td>60</td>
<td>59</td>
<td>51</td>
<td>50</td>
</tr>
<tr>
<td>Sex</td>
<td>Male</td>
<td>Male</td>
<td>Male</td>
<td>Female</td>
<td>Male</td>
</tr>
<tr>
<td>Hand dominance(^\text{\textsuperscript{a}})</td>
<td>Left (consistent)</td>
<td>Right (consistent)</td>
<td>Right (consistent)</td>
<td>Right (consistent)</td>
<td>Right (consistent)</td>
</tr>
<tr>
<td>Affected side</td>
<td>Left</td>
<td>Left</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>Time since stroke onset</td>
<td>10.5 wks</td>
<td>6.5 wks</td>
<td>5.5 wks</td>
<td>13.5 wks</td>
<td>8 wks</td>
</tr>
<tr>
<td>Site of lesion (based on CT scan)</td>
<td>Right frontoparietal infarct</td>
<td>Right temporal lobe, corona radiata, and lentiform nucleus infarct</td>
<td>Left frontoparietal and corona radiata infarct</td>
<td>Left lentiform-internal capsular hemorrhage</td>
<td>Right basal ganglia, internal capsule hemorrhage</td>
</tr>
<tr>
<td>Motor function (affected UL)</td>
<td>Limited voluntary movement</td>
<td>Isolated finger control</td>
<td>No voluntary movement of wrist and fingers</td>
<td>No functional movement</td>
<td>No functional movement</td>
</tr>
<tr>
<td>Sensory function (affected UL)</td>
<td>TDT = 100</td>
<td>TDT = 100</td>
<td>TDT = 100</td>
<td>TDT = 100</td>
<td>TDT = 100</td>
</tr>
<tr>
<td>PSI WPST = 23.9 degrees</td>
<td>PSI WPST = 11.3 degrees</td>
<td>PSI WPST = 32.4 degrees</td>
<td>PSI WPST = 32.7 degrees</td>
<td>PSI WPST = 25.2 degrees</td>
<td>PSI WPST = 25.2 degrees</td>
</tr>
<tr>
<td>Pressure = 6.65</td>
<td>Pressure = 4.31</td>
<td>Pressure = 4.31</td>
<td>Pressure = N/A</td>
<td>Pressure = 6.65</td>
<td>Pressure = 6.65</td>
</tr>
<tr>
<td>H/C = 5/10</td>
<td>H/C = 7/10</td>
<td>H/C = 6/10</td>
<td>H/C = N/A</td>
<td>H/C = 0/10</td>
<td>H/C = 0/10</td>
</tr>
<tr>
<td>Cognitive function</td>
<td>Slight decrease in complex planning skills, otherwise NAD</td>
<td>Impaired language; integrity of problem solving and memory</td>
<td>Mildly reduced attention processes; slow information processing</td>
<td>NAD; alert; concentration, memory, and learning intact</td>
<td>NAD; attention, memory, and learning intact</td>
</tr>
</tbody>
</table>

\( P \) CT scan, computed tomographic scan; UL, upper limb; TDT, Tactile Discrimination Test\(^\text{\textsuperscript{15}}\); PSI, percentage of spatial increase; WPST, Wrist Position Sense Test in flexion-extension plane\(^\text{\textsuperscript{14}}\); Pressure, log\(^\text{\textsuperscript{2}}\) force of Semmes-Weinstein monofilament (in milligrams) detected at preferred finger\(^\text{\textsuperscript{17}}\); H/C, hot/cold discrimination using Roylan hot and cold discrimination kit (A629-1); number of correct judgments out of ten stimuli presented to distal pad of preferred finger are reported; N/A, not available; NAD, no abnormality detected.

\( \text{a} \) Hand dominance determined from Annett\(^\text{\textsuperscript{21}}\) questionnaire of hand dominance.
parallel change in the transfer response, suggesting a specific training effect. Statistical analysis confirmed both trend and level effects in the three series (Table 2). Improvements achieved by the end of the training were well maintained. In the remaining two series, no intervention effect could be claimed (Fig. 1, S04 and S05). Both series showed an improvement during baseline, limiting the scope for training effects.

**Spontaneous Transfer of Training**

Spontaneous transfer of training to the second response was not evident in two of the three cases in which an intervention effect was present in the primary trained response (Fig. 1, S01 and S03). Lack of a concomitant and systematic change in the transfer responses was confirmed by the panel of judges. Although a statistically significant change in trend was obtained for subject 3 (Table 3, S03) the change was not in the therapeutic direction. Subject 2 demonstrated variable performance on the transfer task (FMT) during sessions 1–10 of baseline and a reduced variability and possible improvement during sessions 11–20 of baseline. It was difficult to distinguish whether these observations represented continuation of the pattern established in the first baseline phase or a change in the second baseline phase; therefore, judgment was reserved. The panel of visual analysts failed to indicate a systematic change. However, a statistically

**FIGURE 1** Case charts of spontaneous transfer effects within tactile and proprioceptive domains. In phase 1 (sessions 1–10), performance was monitored under baseline conditions for both trained and transfer stimuli. In phase 2 (sessions 11–20), stimulus-specific training was introduced to the primary trained response (texture grids or flexion-extension wrist positions). Performance of the transfer response (fabrics or ulnar-radial wrist positions) was simultaneously monitored under extended baseline conditions to permit observation of spontaneous transfer effects. In phase 3 (sessions 21–30), stimulus-specific training was introduced to the transfer response and continued for the primary trained response but at a lower intensity. Texture grid limen (PSI), score from the Tactile Discrimination Test in units of percentage of spatial increase.1,5 Fisher’s z-scale was inverted so that graphical representation of the Fabric score was consistent with the Tactile Discrimination Test score (i.e., higher values represent poorer performance). Flex-ext position error (deg), flexion-extension wrist position sense average error, in degrees, based on the Wrist Position Sense Test.1,5 Uln-rad position error (deg), ulnar-radial deviation wrist position sense average error, in degrees, based on the Ulnar-Radial Wrist Position Sense Test.1,5 S01–S05, subjects 1–5.
significant change in level, from 2.6 to 2.1, on the fabric-matching score was observed (Table 3). The identified change was in a therapeutic direction but of small magnitude and did not seem to follow the characteristic logarithmic function. In the remaining two cases (subjects 4 and 5), an intervention effect in the first-trained primary response was not identified; therefore, generalization of a training effect was not testable.

**Effect of SST on the Transfer Stimuli**

Although the fabric and ulnar-radial position stimuli did not demonstrate evidence of spontaneous generalization effects, they did respond to SST.
in all cases (Fig. 1). Improvements were clearly defined and marked relative to the second phase of baseline. All subjects performed within the normal range on the GMT and WPST for ulnar-radial deviation by the end of training. Performance on the FMT varied.

**Study 2**

Background details of subjects are presented in Table 4. Subjects showed severe deficit on the GMT (-0.12 to 0.29 z score compared with 0.62 z score, the criterion of normality) and moderate to severe impairment on the FMT (criterion of normality, >1.61 z score). Most patients had the maximum impairment score on the TDT. Performance on the WPST varied.

**Model Identification**

The logarithmic model previously identified in several of our studies and in study 1 again successfully accounted for baseline and intervention data, leaving no statistically significant or suspiciously high positive autocorrelation in the residuals of any time series.

<table>
<thead>
<tr>
<th>TABLE 4 Background information of subjects in study 2</th>
<th>Subject</th>
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<tbody>
<tr>
<td>S06</td>
<td>S07</td>
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<td>Age, yrs</td>
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<td>Sex</td>
<td>Male</td>
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<tr>
<td>Hand dominance</td>
<td>Right (consistent)</td>
</tr>
<tr>
<td>Affected side</td>
<td>Right</td>
</tr>
<tr>
<td>Time since stroke onset</td>
<td>5 wks</td>
</tr>
<tr>
<td>Site of lesion (CT scan)</td>
<td>Left striatocapsular infarct</td>
</tr>
<tr>
<td>Motor function (affected UL)</td>
<td>No active movement</td>
</tr>
<tr>
<td>Sensory function (affected UL)</td>
<td>GMT = 0.15</td>
</tr>
<tr>
<td>TDT</td>
<td>N/A</td>
</tr>
<tr>
<td>PSI WPST</td>
<td>PSI WPST = N/A</td>
</tr>
<tr>
<td>Cognitive function</td>
<td>Expressive dysphasia</td>
</tr>
</tbody>
</table>

**Cognitive function**

CT scan, computed tomographic scan; UL, upper limb; GMT, Grid Matching Test (Fisher’s z scores); FMT, Fabric Matching Test (Fisher’s z scores); TDT, Tactile Discrimination Test; PSI, percentage of spatial increase; WPST, Wrist Position Sense Test in flexion-extension plane; N/A, not available; NAD, no abnormality detected.

*Hand dominance determined from Annett questionnaire of hand dominance.*

**Effects of SST**

The case charts (Fig. 2) suggested a systematic change between baseline and SST phases for the GMT beyond any parallel change in the transfer responses of each of the subjects. Improvements were marked, often achieving scores within the normal performance range and comparable with the other hand. These effects of SST were confirmed for each subject by the ITSAs (Table 2, S06 to S10).

**Spontaneous Transfer to Untrained Fabric Stimuli After SST**

Spontaneous transfer to the untrained FMT response was not evident in the second baseline phase when SST of texture grids was introduced (Fig. 2). This was clear for subjects 6–8. Subjects 9 and 10 showed more variability. Lack of a transfer effect was confirmed by the results of the ITSA in all but one case (Table 3). A significant trend effect was identified in subject 9. However, the change did not follow the characteristic pattern achieved by training, and performance was variable; thus, a spontaneous transfer effect was not claimed.

**Transfer to Novel Textured Stimuli After SST**

Discrimination of fabric surfaces, which had not been trained in any of the three phases, im-
proved on introduction of the SGT program in four of the five experiments (subjects 6–9), as shown in Figure 2. Improvements were often marked, achieving scores within the normal performance range. They followed a pattern similar to the SST effects, although the magnitude of early change

FIGURE 2  Case charts of stimulus-generalization training effects in the tactile domain. In phase 1 (typically sessions 1–10), performance was monitored under baseline conditions for both trained and transfer stimuli. In phase 2 (typically sessions 11–20), stimulus-specific training (SST) was introduced to the texture grids and spontaneous transfer effects were monitored in the transfer-fabric stimulus. In phase 3 (typically sessions 21–30), stimulus-generalization training (SGT) was introduced, and monitoring continued for the fabric response to permit observation of transfer of training effects. Grid-matching and fabric-matching test scores are in Fisher’s z units. In contrast to Figure 1, higher values represent better performance. Case chart S06: trained/untrained grids provides an example of the case charts in which the grid-matching score was separately calculated for grids that were trained and those that were not trained. Stimulus-specific training effects are evident in the trained grid score, and spontaneous transfer of training effects are evident in the untrained grid score. S06–S10, subjects 6–10.
was often smaller. Subject 10 also showed an improvement trend in phase 3; however, this was not significantly different from the preexisting trend evident in phase 2 (Table 5). Statistical analyses are summarized in Table 5.

**Spontaneous Transfer from Trained to Untrained Grids After SST**

To investigate whether transfer might occur across stimuli with the same texture characteristic, we trained for only half of the grid surfaces, while monitoring performance on all (Fig. 2, S06: **trained/untrained grids**). Spontaneous transfer from trained texture grids to untrained texture grids did occur with the SST program in four of the five case experiments (Table 6). Subject 10 was the only subject who did not show either spontaneous transfer to stimuli with the same distinctive feature (texture grids) or facilitate transfer to novel stimuli (fabrics).

**Meta-analyses**

A meta-analysis investigating the overall effect of SST with the plastic texture grids was performed on the seven subjects providing appropriate data (subjects 1, 2, and 6–10). This meta-analysis very clearly confirmed the positive effect of training on the discrimination of texture grids in both level \( (Z = 7.61, P < 0.001) \) and trend \( (Z = 8.46, P < 0.001) \) variables. Discriminations within the same difficulty range, but using plastic grids with spatial intervals that were not used during training trials, were available from five experiments (subjects 6–10). This meta-analysis also showed significantly improved performance in both the level \( (Z = 3.43, P < 0.001) \) and trend \( (Z = 4.61, P < 0.001) \) variables. These strong positive results in discriminations of trained and untrained texture grids contrast markedly with the results obtained for spontaneous transfer–related changes in the discrimination of fabric textures after SST of plastic grids. Meta-analysis of these time series failed to show a statistically significant effect in either level \( (Z = -0.206, P > 0.41) \) or trend changes \( (Z = 0.126, P > 0.55) \), despite the increase in sensitivity afforded by the pooling of seven sets of experimental results. A meta-analysis that directly contrasted the effect of specific grid training on discrimination of plastic grids vs. discrimination of fabrics showed a clearly superior effect in the discrimination of the plastic grids according to both level \( (Z = 5.24, P < 0.001) \) and trend \( (Z = 6.07, P < 0.001) \) variable results. Importantly, when the SGT program was introduced in the second group of five experiments, both level \( (Z = 4.10, P < 0.001) \) and trend \( (Z = 5.57, P < 0.001) \) variables responded with significant changes in the untrained transfer stimuli.

**DISCUSSION**

Several conclusions seem reasonable. First, rapid, task-specific training effects can be obtained with the SST program. Second, improvements obtained in a particular discrimination task do not generalize spontaneously to related stimuli within the same sensory-perceptual dimension in stroke patients after SST. For example, training on grid surfaces did not generalize to fabrics. However, spontaneous transfer of training does seem to occur across stimuli that share the same distinctive feature (e.g., trained and untrained grids) after SST. Third, performance on related untrained stimuli within the same sensory-perceptual dimension can be improved to a clinically significant degree by using a program deliberately oriented to enhance generalization (the SGT program). Transfer of training from practice with paper, glass, and rubber to discrimination of fabric surfaces illustrates this point.

**Conditions of Training and Influence on Transfer**

Successful transfer across stimuli seems to have been influenced by the training principles employed. The SST program employed principles designed to maximize learning to discriminate a particular stimulus type. Positive training and transfer effects within the specific stimulus type

<p>| TABLE 5 Stimulus-generalization training effect: Transfer to novel textured stimuli |
|---------------------------------|--------|----------|--------|</p>
<table>
<thead>
<tr>
<th>Subject</th>
<th>Time Series</th>
<th>Trend Effect</th>
<th>Level Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>df</td>
<td>Effect</td>
</tr>
<tr>
<td>S06</td>
<td>Fabrics</td>
<td>t(16) = 5.37</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>S07</td>
<td>Fabrics</td>
<td>t(16) = 3.41</td>
<td>&lt;0.002</td>
</tr>
<tr>
<td>S08</td>
<td>Fabrics</td>
<td>t(16) = 4.13</td>
<td>&lt;0.0004</td>
</tr>
<tr>
<td>S09</td>
<td>Fabrics</td>
<td>t(21) = 1.77</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>S10</td>
<td>Fabrics</td>
<td>t(23) = 1.13</td>
<td>&gt;0.05</td>
</tr>
</tbody>
</table>

Bold \( P \) values indicate a significant effect in a therapeutic direction. Comparisons are between the second phase of baseline and the stimulus-generalization training phase for the transfer stimulus.

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trained were achieved. However, spontaneous transfer to related tasks within the same sensory-perceptual dimension did not occur. To facilitate generalized improvements, a program that added variation in training stimuli, intermittent feedback, and tuition of training principles was required. Repeated exposure under conditions of attentive exploration with vision occluded was usually insufficient for therapeutic change, as indicated by stable baseline performance in 75% of the baseline time series investigated. Thus, conditions of training seem important to outcome, with implications for the design of efficient rehabilitation programs. The principles of training derived from studies of learning with normal subjects seem applicable to stroke patients, confirming the value of learning theory for models of neurologic rehabilitation.

**Specificity of Learning and Information Processing Within the Sensory System**

Perceptual learning studies with unimpaired subjects suggest that discrimination training is often highly specific to the task and receptor location and to the method of processing information. We also found highly specific training effects in tasks employing the same sensory dimension (tactile or proprioceptive) and body location (fingertip or wrist) when SST was undertaken. Spontaneous transfer was, however, found across stimuli of the same type that employed the same receptor location and method of processing the information (e.g., from trained to untrained grids and across wrist positions within the same plane of movement [positions trained were different to those assessed]). These findings suggest spontaneous transfer of training to novel stimuli of the same type and of comparable difficulty when SST is employed.

The high degree of specificity observed is also consistent with evidence of highly specific deficits resulting from cerebral damage. Moreover, studies of behaviorally induced neural plasticity suggest that changes in cortical maps are specific to the trained task and specific body location in monkeys and humans. Organization of the somatosensory system is highly specific, as evidenced by body location and modality-specific columnar organization and submodality-specific neurons in the primary somatosensory cortex and neuro-axial tissues. These observations indicate a high degree of specificity of information processing within modalities and body locations. However, the sensory system is also characterized by convergence of somatosensory information and presence of distributed sensory networks. Thus, distinctive sensory features of a multidimensional texture might be integrated in a unified perception at a level of convergence in the system. This level of processing would be consistent with the learning and transfer across textures with multiple features of roughness after SGT.

**What Is Learned**

A common view supported by behavioral and neurophysiologic evidence proposes that distinctive features of difference are learned and form the basis of transfer of training. In the TDT and GMT, the distinctive feature is likely to be the spatial interval of the grids, whereas the physical characteristics of fabrics are likely to be based on nonspatial neural coding mechanisms. This inference is supported by observation of stimulus-specific transfer within, but not across, these stimuli. The distinctive feature of the limb-position task is presumed to be the change in location of the limb or relative wrist angle. Our findings suggest that the distinctive

<table>
<thead>
<tr>
<th>Subject</th>
<th>Texture Grids</th>
<th>Trend Effect</th>
<th>Level Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>S06</td>
<td>Trained</td>
<td>$t(16) = 5.49$</td>
<td>$&lt;0.0001$</td>
</tr>
<tr>
<td></td>
<td>Untrained</td>
<td>$t(16) = 3.02$</td>
<td>$&lt;0.004$</td>
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<tr>
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<td>Trained</td>
<td>$t(16) = 4.70$</td>
<td>$&lt;0.0001$</td>
</tr>
<tr>
<td></td>
<td>Untrained</td>
<td>$t(16) = 3.21$</td>
<td>$&lt;0.003$</td>
</tr>
<tr>
<td>S08</td>
<td>Trained</td>
<td>$t(21) = 4.77$</td>
<td>$&lt;0.0001$</td>
</tr>
<tr>
<td></td>
<td>Untrained</td>
<td>$t(21) = 4.77$</td>
<td>$&lt;0.0001$</td>
</tr>
<tr>
<td>S09</td>
<td>Trained</td>
<td>$t(18) = 5.30$</td>
<td>$&lt;0.0001$</td>
</tr>
<tr>
<td></td>
<td>Untrained</td>
<td>$t(18) = 0.40$</td>
<td>$&gt;0.05$</td>
</tr>
</tbody>
</table>

Bold $P$ values indicate a significant effect in a therapeutic direction. Comparisons are between baseline and stimulus-specific training phases for the trained grids and between the first and second phase of baseline for the untrained grids.
feature also needs to be defined in relation to the defined plane of movement or to receptors involved in the discrimination. This conclusion is consistent with observations indicating selective activation of muscle receptors, joint receptors, and skin areas in association with specific positions. Thus, it seems necessary that the distinctive features of stimulus difference are highly similar and specific to the receptor population activated to obtain spontaneous generalization.

Using the SGT program, transfer was obtained across tactile stimuli with potentially different distinctive features (i.e., from training on rubber, glass, leather, and sandpaper to transfer on fabrics). Training of multidimensional stimuli with a wide range of distinctive features in the SGT program is likely to increase the probability of exposure to distinctive features relevant to the transfer stimulus, with consequent transfer of learning. Investigations with unimpaired subjects have suggested that transfer is facilitated when stimuli are more complex and potentially share some distinctive features. Physical characteristics of difference trained in our study included surface type, surface contour, grit, friction/abrasion, stimulus patterns with different spatial frequencies, surface irregularities, and various combinations of these. This set of features seems to represent a broader dimension of roughness and covers aspects of roughness that are both spatial and nonspatial. Thus, success of the SGT may be influenced by the fact that the varied stimuli used included nonspatial discriminations that may be more directly related to the transfer stimulus. Further, it may be the dimension of roughness, rather than a specific unitary feature of it, that is learned and transferred in this training. Other studies obtaining generalized training effects in stroke patients have included variation in training stimuli, supporting this interpretation.

Generalization of Training Within a Disordered Somatosensory System

The ability of stroke patients to generalize learning to novel tasks is relatively unknown, particularly within the somatosensory domain. Stroke patients with somatosensory impairment may not have the capacity to process the intrinsic somatosensory input from the untrained transfer task or may have a more global difficulty in generalizing learning effects. Our findings confirm both task-specific and generalized transfer effects. The observed effects suggest that stroke patients can transfer learning effects, but the boundaries of transfer do have limits. More importantly, they suggest a high degree of specificity of learning and provide some guidelines on what features of the task need to be similar before learning transfers.

Subjects with an unimpaired sensory system can improve perceptual discriminations with practice alone and demonstrate spontaneous perceptual transfer. In contrast, stroke patients in the present studies repeatedly practiced with the assessment stimuli during baseline, yet in the majority of cases, they did not demonstrate improvement on these stimuli. This finding highlights the need for appropriate conditions in rehabilitation training. Repeated exposure alone, which approximates exposure to sensory stimuli in daily activities, was not adequate to effect a clinically significant improvement.

After damage to somatosensory cortical areas and their connections, it is likely that stroke patients have an inadequate foundation from which to perceive and discriminate novel stimuli, although they may have learned the principles of how to process similar types of information better. Perceptual learning at any given time is constrained by the existing structure. Evidence that learning involves modification of representations in the brain suggests that perceptual training is not only a means of training the process of perceptual learning. Individuals must have access to the distinctive characteristic of the stimulus to extract the distinctive feature. External quantitative feedback on what is being perceived may be necessary to make sense of or to “calibrate” perceptions in a changed (e.g., after brain damage) system.

Study Limitations

Investigation of training effects was limited to ten subjects (20 time series). Although this is a small number for group-based studies, each intensive single case is a controlled experiment involving within-subject control and replication of training effects. This approach is well suited to the heterogeneous nature of stroke and allows for variable findings across individuals that might be obscured with group analysis. In addition, systematic replication of training effects across ten subjects with different background characteristics and across tactile and proprioceptive modalities provides generalizability of findings not usually afforded to single case studies. Finally, meta-analysis of individual experiments improves power, permits an overall conclusion, and provides a quantitative evaluation of the generality of treatment effects. Thus, our findings provide a strong foundation for larger controlled studies.

The sequence of baseline, SST, and SGT was constant, and therefore, it may be argued that the exposure and SST phases led to an overlearning effect with an impact on transfer and effectiveness.
of the SGT program. However, this explanation is unlikely given that observed SST effects worked quickly, that even prolonged exposure (e.g., 20 sessions) did not effect changes, and that changes observed for SGT were of similar rapidity. These observations support the conclusion that improvements in the SGT phase were due to a generalization training effect, rather than due to additional dosage of stimulus exposure, or SST.

Implications for Therapeutic Interventions and Further Investigations

Clinically significant improvements were obtained with training, providing justification for therapeutic intervention. Practice or exposure alone was not usually sufficient to achieve the changes characteristic of perceptual learning. The findings also suggest that the nature of training is crucial to outcome. SST may be important if there is a need to train specific work or daily living tasks. However, to facilitate more generalized improvements and minimize reliance on resource-intensive, task-specific training, a program that also includes variation within and across related training stimuli, intermittent feedback, and tuition of training principles is recommended. In the majority of cases, ten training sessions seem to be sufficient to achieve clinically significant improvement. However, the goal of healthcare providers is not only to provide an effective training program but also an efficient training program. The highly specific nature of training suggests that clinicians need to accurately identify the specific sensory dimension that requires training and use graded stimuli that cover the range of distinctive features for the perceptual dimension targeted. Programs cannot rely on spontaneous transfer; they need to systematically train for transfer. This issue of generalization of training effects has importance in relation to rehabilitation of a range of abilities in stroke patients and to rehabilitation in general.

The present studies provide some guidance on both the nature of transfer expected and on the conditions of training required to achieve transfer. Further systematic investigation of these variables is indicated. For example, transfer across macrospatial and microspatial features of surfaces will help to determine if the boundary of spontaneous transfer is at the level of a particular spatial pattern or broader spatial features of roughness. Transfer across dimensions such as smoothness–roughness, hardness–softness, and compressional elasticity within multidimensional texture stimuli is also indicated, particularly after SGT. Investigation of transfer across different joints of the upper limb for proprioception or different fingers for texture is also necessary. Identification of sites of cerebral reorganization underlying the recovery of somatosensory function after stroke may provide new insights into cerebral networks involved in perceptual learning and recovery. Systematic investigation of the relative contribution of training principles in the treatment package would also help to identify the critically important elements associated with successful learning and transfer. 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.

ACKNOWLEDGMENTS

We thank the participants for their involvement in the study and the therapists and management at Royal Talbot Rehabilitation Centre, Cedar Court Healthsouth Rehabilitation Hospital, and Hampton Rehabilitation Hospital, Victoria, Australia, for their support.

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