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Sensory adaptation to electrical stimulation of the somatosensory nerves

Emily L Graczyk[1,2,4], **Benoit P Delhaye**[3,4], **Matthew A Schiefer**[1,2], **Sliman J Bensmaia**[3] **and Dustin J Tyler**[1,2,5]

[1] Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH 44106, United States of America
[2] Cleveland Louis Stokes Department of Veteran's Affairs Medical Center, Cleveland, OH 44106, United States of America
[3] Department of Organismal Biology and Anatomy, University of Chicago, Chicago, IL 60637, United States of America

E-mail: dustin.tyler@case.edu

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Abstract

Objective. Sensory systems adapt their sensitivity to ambient stimulation levels to improve their responsiveness to changes in stimulation. The sense of touch is also subject to adaptation, as evidenced by the desensitization produced by prolonged vibratory stimulation of the skin. Electrical stimulation of nerves elicits tactile sensations that can convey feedback for bionic limbs. In this study, we investigate whether artificial touch is also subject to adaptation, despite the fact that the peripheral mechanotransducers are bypassed. *Approach.* Using well-established psychophysical paradigms, we characterize the time course and magnitude of sensory adaptation caused by extended electrical stimulation of the residual somatosensory nerves in three human amputees implanted with cuff electrodes. *Main results.* We find that electrical stimulation of the nerve also induces perceptual adaptation that recovers after cessation of the stimulus. The time course and magnitude of electrically-induced adaptation are equivalent to their mechanically-induced counterparts. *Significance.* We conclude that, in natural touch, the process of mechanotransduction is not required for adaptation, and artificial touch naturally experiences adaptation-induced adjustments of the dynamic range of sensations. Further, as it does for native hands, adaptation confers to bionic hands enhanced sensitivity to changes in stimulation and thus a more natural sensory experience.

Keywords: electrical stimulation, sensory adaptation, psychophysics, neuroprosthetics, sensory neuroscience, peripheral nerve stimulation, somatosensation

(Some figures may appear in colour only in the online journal)

Introduction

Adaptation—the progressive desensitization to prolonged, suprathreshold stimulation—is a ubiquitous phenomenon in the nervous system, one that has been extensively documented in all sensory systems. For example, vision is far more sensitive in the dark than it is in daylight (Hecht 1920). The function of adaptation is to adjust sensitivity to reduce responsiveness to ambient stimulation levels and to promote responsiveness to changes in stimulation (Brenner *et al* 2000). Visual adaptation is a key reason why we can see across eight orders of magnitude of ambient illumination.

The sense of touch is also subject to adaptation, as evidenced by the progressive perceptual and neuronal desensitization caused by prolonged vibrotactile stimulation of the skin. In psychophysical experiments, suprathreshold vibrotactile stimulation results in an increase in detection threshold and a progressive decrease in the subjective magnitude of the

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[4] These authors contributed equally to this work.
[5] Author to whom any correspondence should be addressed.

stimulus (Hahn 1966, Gescheider and Wright 1968, Berglund and Berglund 1970, Verrillo and Gescheider 1977, Hollins *et al* 1990). The degree of adaptation increases as the amplitude of the conditioning stimulus increases and also depends on its frequency (Verrillo and Gescheider 1977, Hollins *et al* 1990). The frequency-dependence of adaptation reflects, in part, the frequency-sensitivity profiles of the different classes of tactile nerve fibers: fibers that are more sensitive to a stimulus will tend to be more desensitized by it. Higher frequencies also tend to adapt nerve fibers more strongly (Hollins *et al* 1990, Bensmaïa *et al* 2005).

Vibrotactile adaptation is caused in part by changes in skin elasticity that impact the transmission of vibrations through the skin (Hahn 1966). However, a major contributor to vibrotactile adaptation is a desensitization of the nerve fibers themselves, caused by a progressive increase in their spike-generation threshold (Ribot-Ciscar *et al* 1996, Bensmaïa *et al* 2005). Finally, central desensitization also plays a role in the observed perceptual adaptation as evidenced by the fact that the latter operates on a slower time scale than does its neuronal counterpart at the periphery (Leung *et al* 2005).

While adaptation has been extensively documented for natural tactile stimulation, less is known about whether direct activation of neurons through electrical stimulation also leads to adaptation. Indeed, sensory adaptation has been shown to occur with electrocutaneous stimulation (Szeto and Saunders 1982, Kaczmarek *et al* 1991, Kaczmarek 2000, Buma *et al* 2007), but this effect may be, at least in part, mediated by a desensitization of the mechanotransduction sites. Characterizing adaptation when mechanoreceptors are bypassed is important for understanding the mechanism of adaptation and for the development of bionic limbs for amputees that provide artificial tactile feedback by electrically stimulating the nerve through chronically implanted neural interfaces. Patterned electrical stimulation of the nerve has been shown to evoke tactile percepts and improve the performance of hand prosthesis users on functional tasks (Clark *et al* 2014, Raspopovic *et al* 2014, Tan *et al* 2014, Graczyk *et al* 2016, Oddo *et al* 2016, Schiefer *et al* 2016). Having previously observed that extraneural stimulation of the nerve seems to cause adaptation (Graczyk *et al* 2016), we sought in the present study to assess its magnitude, its dependence on stimulation parameters, and its time course using well-established psychophysical experimental paradigms. We then compare the effects of adaptation on artificial touch to those observed with natural tactile stimulation and discuss the implications of our results on the design of sensory encoding algorithms for bionic hands.

Methods

Subjects

Three male human volunteers with unilateral, upper limb loss (two right arm and one left arm) participated in this study. Subject 1 has a right trans-radial amputation due to a traumatic injury in 2010 and was implanted with two 8-contact flat interface nerve electrodes (FINEs) around his median and ulnar nerves and a 4-contact CWRU spiral electrode around his radial nerve in 2012. Subject 2 has a right trans-radial amputation due to a traumatic injury in 2004 and was implanted with three 8-contact FINEs around his median, ulnar, and radial nerves in 2013. Subject 3 has a left trans-radial amputation due to a traumatic injury in 2013 and was implanted with two 16-contact FINEs around his median and ulnar nerves in 2016. The subjects came to the laboratory for 6 h testing sessions every 2–6 weeks, depending on their availability. The present study took place in months 47 to 62 post-implantation for subject 1, months 38 to 54 post-implantation for subject 2, and month 15 post-implantation for subject 3. All study devices and procedures were reviewed and governed by the U.S. Food and Drug Administration Investigational Device Exemption, the Cleveland Department of Veterans Affairs Medical Center Institutional Review Board, and the Department of the Navy Human Research Protection Program. Informed consent was obtained from all subjects.

Electrical stimuli

Trains of square, bi-phasic, current-controlled, cathode-first stimulation pulses were delivered to individual contacts on the electrodes. The projected location and quality of the sensations evoked by the stimulation paradigms used in this study have been previously described in detail (Tan *et al* 2014, Graczyk *et al* 2016). In brief, subjects reported tactile and proprioceptive sensations and used words such as ‘pressure’, ‘vibration’, ‘touch’, ‘tingling’, ‘contraction’, or ‘movement’ to describe them.

Detection thresholds

Before starting the experiment, a rough estimate of the subject’s detection threshold was obtained. Pulse frequency (PF) was set to 100 Hz, pulse width (PW) to 255 μs, and pulse amplitude (PA) to 0.3 mA, and each stimulation train lasted for 5 s. Because the PA resolution of our stimulator was fairly coarse and we aimed to operate stimulation on the right side of the strength-duration curve, we first increased PA until sensation was reported, then decreased PW to find the detection threshold. PA was increased in steps of 0.1 mA in successive trials until sensation was reported. A two-alternative forced-choice tracking paradigm was used to find the minimum detectable PW at this PA: starting at 130 μs, PW was decremented by $130/2^n$ when the subject reported sensation or incremented by this same amount when the subject did not (where n is the number of reversals). To allow a sufficient range of PWs above threshold for the conditioning stimulus (described below), if the minimum detectable PW was greater than 150 μs, the PA was increased again by 0.1 mA and the tracking paradigm was repeated to find the minimum detectable PW at this new PA. This process was repeated until the minimum detectable PW was below 150 μs. This threshold estimation served as an initial starting point for the experiments described below. In addition, PWs in the experimental

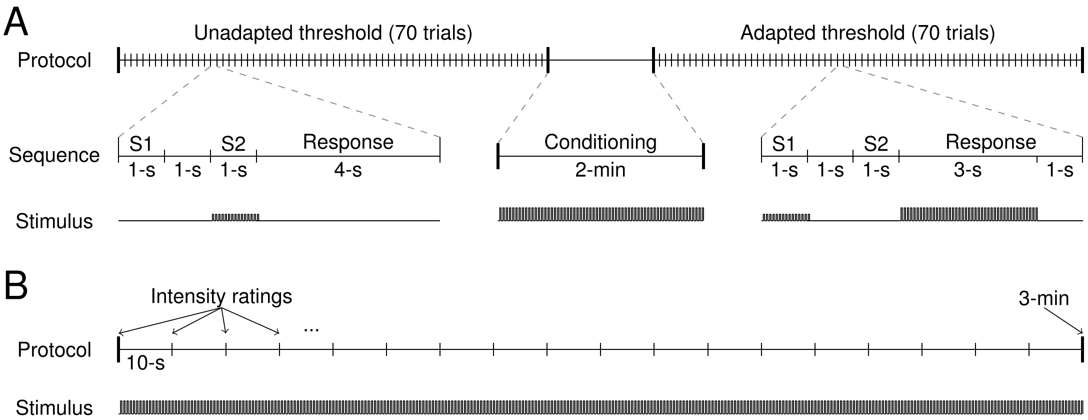

Figure 1. Experimental protocols. (A) The detection threshold experiment: the detection threshold was measured before and after a 2 min conditioning stimulus. In each trial sequence, two 1-s stimulus intervals were presented with a 1-s intervening period. Only one interval contained a stimulus and the location of the stimulus in interval 1 or 2 was randomized. The response interval was 4 s long and contained a 3-s 'boost' of the conditioning stimulus in the adapted threshold trials, but not in the unadapted threshold trials. (B) The intensity tracking experiment: the intensity of a constant stimulus was rated every 10 s for 3 min.

range were briefly tested to ensure that all sensations were comfortable.

A single experimental block consisted of first finding the unadapted detection threshold, then administering a suprathreshold conditioning stimulus for 2 min, then finding the adapted threshold (figure 1(A)). Thresholds in the experimental block were measured by the method of constant stimuli (Gescheider 1997), with each threshold measurement consisting of 70 trials. On each trial, two sequential stimulus intervals were indicated by a visual display, each lasting 1 s with a 1-s inter-stimulus interval. One of the intervals contained a stimulus and the subject's task was to indicate which one by pressing one of two keys. A 4-s inter-trial interval was enforced, which included the response time. Seven PWs spaced over a broad range were each tested ten times in pseudo-random order. Whether the stimulus was presented in the first or second interval was randomized. The same set of PWs was tested for both the unadapted and adapted thresholds. On adapted trials, the conditioning stimulus was presented during the first three seconds of the 4-s inter-trial interval to maintain the level of adaptation. Each experimental block lasted approximately 30 min.

This procedure was repeated for twelve electrode contacts in two subjects (subjects 1 and 2) and in six different experimental sessions (two contacts per session). Four to six experimental blocks were administered per session, with the electrode contacts interleaved to allow for recovery from adaptation between successive blocks. To determine the effect of the conditioning stimulus intensity on threshold shift, one parameter of the conditioning stimulus (either PW or PF) was systematically varied across three different levels within a single experimental session, while the other conditioning stimulus parameters were held constant. When PW was varied (eight contacts), the PF was fixed at 100 Hz and the conditioning stimuli took on one of three values of PW: low (~10–50 μs above detection threshold), mid (~50–100 μs above detection threshold), or high (~100–150 μs above detection threshold). When PF was varied (four contacts), the PW was fixed at a suprathreshold value and the PF of the conditioning stimulus was 25, 50, or 200 Hz.

The proportion of correct detections as a function of PW was described by a normal cumulative density function, fit using Bayesian inference methods (psignifit 3.0 Matlab toolbox, see Fründ *et al* (2011). The detection threshold is the PW corresponding to 75% correct performance. The adaptation effect for each block is the magnitude of the threshold elevation caused by the conditioning stimulus. For the purposes of inference testing, we computed the z-score of the adaptation effects obtained from each lead to pool data across leads.

Intensity tracking

First, a rough estimate of the detection threshold was found as described above and a comfortable range of supra-threshold test PWs was chosen. Then, the test (supra-threshold) stimulus was presented to the subject with constant PW, PA, and PF for 3 min without interruption (figure 1(B)). Every ten seconds, an auditory cue signaled the subject to indicate the perceived magnitude of the sensation on a visual-analog scale presented on a computer screen. Each stimulus was presented three times. In a single experimental session, four electrode contacts were tested in interleaved order, to allow for recovery from adaptation between successive tests of the same lead. The contacts tested within a session were selected to be as far apart in the cuff as possible and such that the projected fields did not overlap to minimize the likelihood that overlapping fiber populations were activated in consecutive test blocks. To test the effect of PW and PF on adaptation, several different supra-threshold PWs (2–4 suprathreshold PWs) or PFs (25, 50, 100 and/or 200 Hz) were presented on separate trials within a single experimental session. A total of 24 contacts were tested in 14 sessions across three subjects, yielding a total of 295 trials.

Perceived intensity, tracked every ten seconds during 3 min, was expressed as a percentage of initial perceived intensity. The percent intensity as a function of time was fit with a piecewise function, using *lsqcurvefit* in Matlab. In the first part of the function, the intensity is a constant set to 100% for a variable duration, typically lasting around 10 s, as this is the period characterized by no discernible adaptation. In the second part, the intensity follows an exponential decay, captured by the following function:

$$I\left(t\right)=\begin{cases}100\%, & t<d\\ A*\mathrm{e}^{\left(\frac{-\left(t-d\right)}{\tau}\right)}+\left(100-A\right), & t\geqslant d\end{cases}$$

where A is the magnitude of the intensity decay (in %), τ is the time constant (in seconds) and d is a delay that captures the duration of the first part (in seconds). A, τ, and d are free parameters. Time constant estimates are highly sensitive to noisy data. With this in mind, we discarded trials in which traces were poorly fit by an exponential ($R^2 < 0.7$). We also discarded trials where decay was extreme ($A < 10\%$ or $A > 95\%$) because these also yielded poor estimates of the time constants. Time constants were transformed logarithmically for the purposes of inference testing because they were log-normally distributed.

Experimental design and statistical analysis

For the detection threshold experiments, adapted thresholds were compared to unadapted thresholds using paired t-tests. Pearson's correlation coefficients were used to determine the impact of conditioning stimulation levels on threshold elevation. For the intensity tracking experiments, perceived intensity at the end of the trials was compared to initial intensity using a one-sample t-test. Pearson's correlation coefficients were used to determine the impact of stimulation PW and PF on decay rate and decay amplitude. Within-trial comparisons between stimulation levels were performed using paired t-tests. All statistical tests were performed in Matlab with alpha level set to 0.05.

Results

Detection thresholds

First, we examined the degree to which perceptual sensitivity to electrical stimulation of the nerve is affected by extended supra-threshold electrical stimulation. Sensitivity was quantified by the detection threshold using a standard two-alternative forced choice paradigm (figure 1(A)). Threshold estimates obtained before the application of a conditioning stimulus were consistent across blocks (figure 2, black traces). This confirms that the approach provided reliable threshold estimates and that thresholds recover to baseline following periods of no stimulation. The same threshold paradigm was then repeated after administering a conditioning stimulus for 2 min. In all cases, the conditioning stimulus reduced perceptual sensitivity to electrical stimulation, as shown by a systematic rightward shift in the psychometric functions and an increase in detection thresholds (see figure 2, red traces, and figure 3(A)). The adapted threshold was significantly greater than the corresponding unadapted threshold in 33 of 36 experimental blocks, and this effect was highly significant (pooled data across sessions and subjects, paired t-test, $t(35) = 10.21$, $p \ll 0.001$). The magnitude of the threshold elevation increased as the PW or PF of the conditioning stimulus increased, as evidenced by a significant correlation between the PW or PF of the conditioning stimulus and threshold shift ($r = 0.76$, $p \ll 0.001$, $n = 25$, for the PW manipulations, see figure 3(B); $r = 0.89$, $p < 0.001$, $n = 11$, for the PF manipulations, see figure 3(C)).

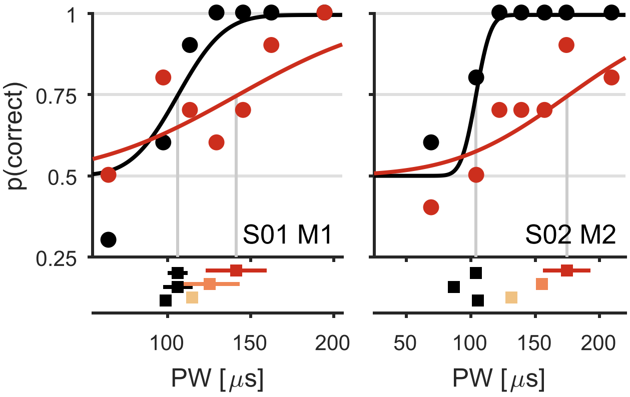

Figure 2. Detection thresholds: top, two typical psychometric functions showing the subject's detection performance as a function of PW (for two different subjects and contacts, indicated at the bottom right of each plot). Black traces indicate unadapted threshold measurements and colored traces indicate adapted threshold measurements. Red traces show the shifted psychometric function for the highest conditioning stimulus intensity. Bottom, the subjects' detection thresholds for three different conditioning intensities (light to dark for low to high conditioning stimulus intensities, respectively). Error bars show 95% confidence intervals.

Intensity tracking

Next, we examined the time course of adaptation. Subjects rated the perceived intensity of a constant stimulus every ten seconds for the duration of the stimulus, which lasted 180 s (figure 1(B)). The perceived intensity decreased significantly over the duration of the stimulus (figure 4, mean decay = 65.01%, $t(203) = 41.39$, $p \ll 0.001$). Indeed, after a short delay (median of 11 s), intensity decayed approximately exponentially with a median time constant of 30 s (figure 5(A)). Fitted time constants were consistent across contacts within subject, but varied across subjects (figure 5(A)). From examination of the aggregate data, time constants seemed to be only weakly dependent on stimulus intensity: τ increased slightly with increases in PW ($r = 0.20$, $p = 0.007$, $n = 174$, figure 5(B)) but was nearly independent of PF ($r = -0.04$, $p = 0.53$, $n = 204$, figure 5(C)). However, on sessions that included trials at different stimulation intensity levels (varying either PW or PF, with all other parameters kept constant), no trends were observed (paired t-test, $t(9) = -0.81$, $p = 0.44$ for PW; $t(20) = 0.16$, $p = 0.88$ for PF, 25 Hz compared to 200 Hz, see lines in figures 5(B) and (C)), suggesting that the effect observed in the aggregate data is artefactual. Furthermore, there was no correlation between stimulation parameters and the degree of decay ($r = 0.04$, $p = 0.61267$, $n = 174$, for PW and $r = -0.13$, $p = 0.06579$, $n = 204$, for PF).

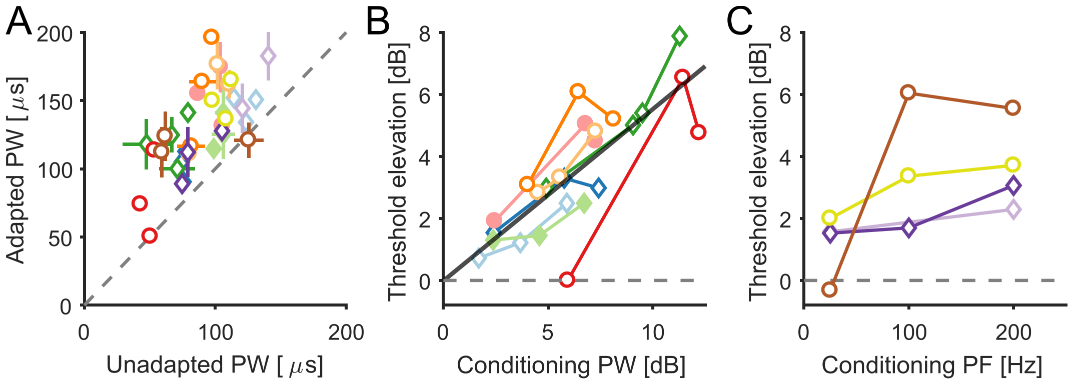

Figure 3. Conditioning stimuli caused an increase in subjects' detection thresholds. (A) Adapted detection threshold as a function of unadapted threshold. Horizontal and vertical bars indicate 95% confidence intervals. (B) Detection threshold elevation as a function of conditioning PW above unadapted threshold (in dB). (C) Detection threshold elevation as a function of conditioning PF (in Hz). Colors indicate different contacts and correspond across (A)–(C); symbols indicate different subjects (circle for S01 and diamond for S02) and filled symbols correspond to examples shown in figure 1.

Discussion

Comparison with natural vibrotactile adaptation

Time course of adaptation. When the skin is subjected to prolonged vibrotactile stimulation, tactile fibers become desensitized over an exponential time course with a time constant of about 10 s (Leung *et al* 2005). In contrast, the decay time constant for vibrotactile perception is slower, ranging from 60 to 200 s based on threshold measurements (Hahn 1966, 1968, Hollins *et al* 1990, 1991) and 20–400 s based on measurements of perceived intensity (Hahn 1966, Berglund and Berglund 1970). The time course of electrically induced sensory adaptation reported here, ranging from 10 to 100 s, thus spans the same range as its vibrotactile counterpart. Comparable time constants, spanning 30 to 200 s, have been observed for electrocutaneous adaptation (Buma *et al* 2007). Although there were subject-specific differences in time constants, these differences did not correspond with time since electrode-implant or with location of electrode contacts relative to the nerve. Furthermore, the observed across-subjects variability in time course has also been reported in the vibrotactile literature (Berglund and Berglund 1970). Therefore, electrically induced adaptation operates over a similar time course as its mechanically induced counterpart.

Effect of adapting amplitude. For vibrotactile stimulation, threshold shift is a power function of conditioning stimulus intensity relative to threshold, with an exponent ranging from 0.5 to 0.7 (Hahn 1966, Verrillo and Gescheider 1977, Hollins *et al* 1990). Similarly, we observed a power function relating threshold and conditioning stimulus intensity (PW), as evidenced by a linear relationship plotted in log-log coordinates, with a slope of 0.55 (see also figure 5(B)). Increasing the amplitude of a vibratory stimulus applied to the skin and increasing the width of electrical pulses in a stimulation train both result primarily in the recruitment of additional nerve fibers (Johnson 1974, Muniak *et al* 2007), which explains why these two manipulations have similar adaptation effects.

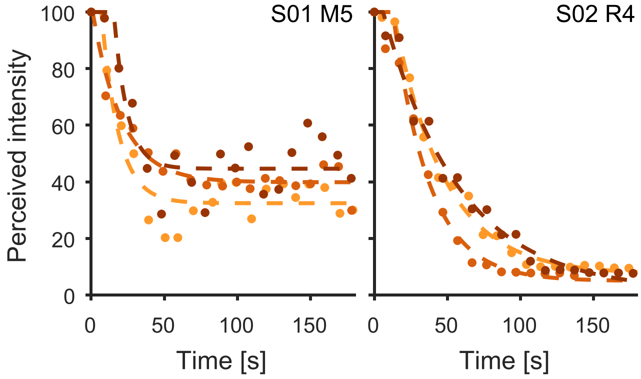

Figure 4. Intensity tracking: two typical experimental data sets for two different subjects (S01 and S02, indicated in upper right of each plot). Perceived intensity with respect to initial perceived intensity as a function of time for three successive trials. Colors indicate the sequence of trials (bright first, dark last). Dots are raw data, dashed lines show exponential fits.

Effect of adapting frequency. For vibrotactile stimulation, the dependence of adaptation effects on frequency can be explained in terms of the frequency sensitivity of the different afferent populations, determined primarily by their mechanoreceptors (Cauna *et al* 1966, Loewenstein and Skalak 1966, Iggo and Ogawa 1977). The extent to which a conditioning stimulus activates a given population of afferents determines the extent to which these will become adapted (Gescheider and Wright 1968, Verrillo and Gescheider 1977, Hollins *et al* 1990). For example, high-frequency stimulation (~250 Hz) selectively desensitizes PC fibers whereas low-frequency stimulation (~10 Hz) primarily desensitizes SA1 and RA fibers. However, higher vibrotactile frequencies also tend to result in greater adaptation effects on individual nerve fibers, over the range of frequencies to which the fiber is sensitive (Bensmaïa *et al* 2005). In contrast, increasing the frequency of an electrical pulse train leads to an increase in the firing rate of all stimulated fibers, regardless of submodality. As a result, increased PF leads to increased thresholds across the entire range of frequencies. Differences in the effect of frequency on electrically and mechanically induced adaptation can thus be

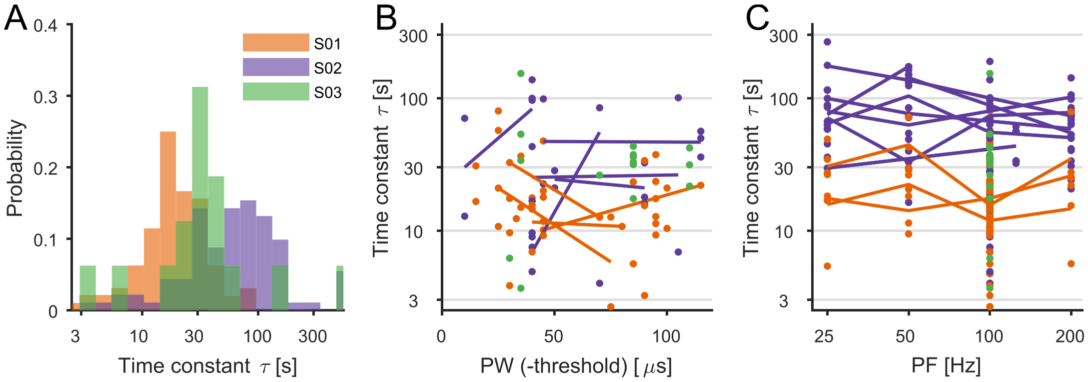

Figure 5. Intensity decay time constants. (A) Histogram for the time constant parameter for the three subjects, all trials pooled. (B) Time constants plotted as a function of stimulus PW (above threshold). For these trials, PF = 100 Hz. (C) Time constants plotted as a function of stimulus PF. For (B) (and (C)), each dot is a single trial and lines are added when multiple PW (in (B)) or PF (in (C)) were tested on the same contact and in the same session (with all other parameters constant). The lines show the average across repetitions for a given PW (or PF). In all three subpanels, colors correspond to different subjects and the time constants are shown on a logarithmic scale.

explained by the different ways in which frequency impacts the evoked neural response in the two modalities.

Implications for the mechanism of adaptation

The parsimonious explanation for the remarkable similarity in the time courses and action spectra of mechanically and electrically induced adaptation is that they are mediated by the same neural mechanisms. Given that electrical stimulation of the nerve bypasses the mechanoreceptors, we can conclude that the process of mechanotransduction is not necessary for perceptual adaptation to occur. Thus, both electrically-induced and mechanically-induced adaptation are not governed by the process of mechanotransduction, but rather by a downstream mechanism, for example an increase in spike generation threshold or synaptic mechanisms in the central nervous system, consistent with previous conjecture (O'Mara *et al* 1988, Bensmaïa *et al* 2005, Whitsel *et al* 2003).

Implications for neuroprosthetics

During sustained grasp with a bionic hand, the nerve may be electrically stimulated for extended periods of time. The resulting progressive desensitization to stimulation may be interpreted as a result of stimulation-induced injury of neural fibers. However, as with its mechanically-induced counterpart, electrically-induced adaptation is reversible and sensitivity returns to its unadapted state minutes after stimulation ceases, as demonstrated by the close similarity in unadapted detection thresholds across successive blocks of threshold measurements (see figure 2). Furthermore, one might decide to compensate for the resulting desensitization by progressively increasing the gain of the stimulator in a stimulation-dependent manner. However, adaptation to natural stimulation is adaptive in the sense that it diminishes the response to constant and therefore uninformative stimulation and renders the nervous system more responsive to *changes* in stimulation, which are more informative (Brenner *et al* 2000). The remarkable similarities between electrically-induced adaptation and its mechanical counterpart suggest that no compensation in electrical stimulation is necessary: the dynamic range of the nerve response will shift according to mean level of stimulation in the same way with electrical stimulation as it would with mechanical stimulation, thereby maximizing the usefulness and naturalness of this artificial somatosensory input. Electrically induced adaptation thus invokes similar neural mechanisms as natural adaptation and closely mimics the function of natural adaptation, enabling more responsive and functional sensory prostheses.

Conclusions

Our study is the first to systematically investigate sensory adaptation for direct electrical stimulation of the peripheral nerve. We find that electrical adaptation of artificial touch shares the same magnitude and time course as vibrotactile adaptation of natural touch. This result has two important implications: from a basic science perspective, it demonstrates that mechanotransduction is not required for tactile adaptation, which means that a downstream mechanism governs adaptation in both natural and artificial touch, a result that will guide future investigations of the cellular mechanisms of adaptation in the nervous system. From a neuroprosthetics standpoint, it shows that adaptation caused by electrical stimulation is beneficial to bionic touch through peripheral interfaces. Indeed, since artificial touch is subject to the same adaptation as is natural touch, the former will benefit from the same enhanced sensitivity to changes in stimulation as does the latter. Neural engineers can thus embrace this phenomenon rather than counteracting it by, for example, dynamically modulating the gain of the stimulator. Further, these parallels between natural and artificial touch contribute to the growing body of evidence that electrical stimulation activates neural pathways in a way that is broadly similar to natural stimulation.

Acknowledgments

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Competing interests

The authors declare no financial competing interests. D J T has patents on the electrodes (US Patent #6456866B1). D J T and M A S have patents on stimulation patterns related to sensory restoration (US Patent #9421366B2). D J T, E L G, B P D, M A S, and S J B also have a patent application on stimulation patterns related to sensory restoration (PCT/US2017/056070).

ORCID iDs

Emily L Graczyk https://orcid.org/0000-0003-1467-8616
Benoit P Delhaye https://orcid.org/0000-0003-3974-7921
Dustin J Tyler https://orcid.org/0000-0002-2298-8510

References

Bensmaïa S J, Leung Y Y, Hsiao S S and Johnson K O 2005 Vibratory adaptation of cutaneous mechanoreceptive afferents *J. Neurophysiol.* **94** 3023–36

Berglund U and Berglund B 1970 Adaptation and recovery in vibrotactile perception *Percept. Mot. Skills* **30** 843–53

Brenner N, Bialek W and de Ruyter van Steveninck R 2000 Adaptive rescaling maximizes information transmission *Neuron* **26** 695–702

Buma D G, Buitenweg J R and Veltink P H 2007 Intermittent stimulation delays adaptation to electrocutaneous sensory feedback *IEEE Trans. Neural Syst. Rehabil. Eng.* **15** 435–41

Cauna N 1966 Fine structure of the receptor organs and its probable functional significance *Ciba Foundation Symposium–Touch, Heat and Pain* (New York: Wiley) pp 117–27

Clark G A, Wendelken S, Page D M, Davis T, Wark H A C, Normann R A, Warren D J and Hutchinson D T 2014 Using multiple high-count electrode arrays in human median and ulnar nerves to restore sensorimotor function after previous transradial amputation of the hand *2014 36th Annual Int. Conf. of the IEEE Engineering in Medicine and Biology Society (EMBC 2014)* pp 1977–80

Fründ I, Haenel N V and Wichmann F A 2011 Inference for psychometric functions in the presence of nonstationary behavior *J. Vis.* **11** 16

Gescheider G A 1997 *Psychophysics: The Fundamentals* 3rd edn (Mahway, NJ: Lawrence Erlbaum Associates, Inc.)

Gescheider G A and Wright J H 1968 Effects of sensory adaptation on the form of the psychophysical magnitude function for cutaneous vibration *J. Exp. Psychol.* **77** 308–13

Graczyk E L, Schiefer M A, Saal H P, Delhaye B P, Bensmaia S J and Tyler D J 2016 The neural basis of perceived intensity in natural and artificial touch *Sci. Trans. Med.* **8** 362ra142

Hahn J F 1966 Vibrotactile adaptation and recovery measured by two methods *J. Exp. Psychol.* **71** 655–8

Hahn J F 1968 Low-frequency vibrotactile adaptation *J. Exp. Psychol.* **78** 655–9

Hecht S 1920 The dark adaptation of the human eye *J. Gen. Physiol.* **2** 499–517

Hollins M, Delemos K A and Goble A K 1991 Vibrotactile adaptation on the face *Percept. Psychophys.* **49** 21–30

Hollins M, Goble A K, Whitsel B L and Tommerdahl M 1990 Time course and action spectrum of vibrotactile adaptation *Somatosens. Mot. Res.* **7** 205–21

Iggo A and Ogawa H 1977 Correlative physiological and morphological studies of rapidly adapting mechanoreceptors in cat's glabrous skin *J. Physiol.* **266** 275–96

Johnson K O 1974 Reconstruction of population response to a vibratory stimulus in quickly adapting mechanoreceptive afferent fiber population innervating glabrous skin of the monkey *J. Neurophysiol.* **37** 48–72

Kaczmarek K A 2000 Electrotactile adaptation on the abdomen: preliminary results *IEEE Trans. Rehabil. Eng.* **8** 499–505

Kaczmarek K A, Webster J G, Bach-y-Rita P and Tompkins W J 1991 Electrotactile and vibrotactile displays for sensory substitution systems *IEEE Trans. Biomed. Eng.* **38** 1–16

Leung Y Y, Bensmaia S J, Hsiao S S and Johnson K O 2005 Time-course of vibratory adaptation and recovery in cutaneous mechanoreceptive afferents *J. Neurophysiol.* **94** 3037–45

Loewenstein W R and Skalak R 1966 Mechanical transmission in a Pacinian corpuscle. An analysis and a theory *J. Physiol.* **182** 346–78

Muniak M A, Ray S, Hsiao S S, Dammann J F and Bensmaia S J 2007 The neural coding of stimulus intensity: linking the population response of mechanoreceptive afferents with psychophysical behavior *J. Neurosci.* **27** 11687–99

O'Mara S, Rowe M J and Tarvin R P 1988 Neural mechanisms in vibrotactile adaptation *J. Neurophysiol.* **59** 607–22

Oddo C M *et al* 2016 Intraneural stimulation elicits discrimination of textural features by artificial fingertip in intact and amputee humans *Elife* **5** 1–27

Raspopovic S *et al* 2014 Restoring natural sensory feedback in real-time bidirectional hand prostheses *Sci. Trans. Med.* **6** 222ra19

Ribot-Ciscar E, Roll J P, Tardy-Gervet M F and Harlay F 1996 Alteration of human cutaneous afferent discharges as the result of long-lasting vibration *J. Appl. Physiol.* **80** 1708–15

Schiefer M, Tan D, Sidek S M and Tyler D J 2016 Sensory feedback by peripheral nerve stimulation improves task performance in individuals with upper limb loss using a myoelectric prosthesis *J. Neural Eng.* **13** 16001

Szeto A Y J and Saunders F A 1982 Electrocutaneous stimulation for sensory communication in rehabilitation engineering *IEEE Trans. Biomed. Eng.* **BME-29** 300–8

Tan D W, Schiefer M A, Keith M W, Anderson J R, Tyler J and Tyler D J 2014 A neural interface provides long-term stable natural touch perception *Sci. Trans. Med.* **6** 257ra138

Verrillo R T and Gescheider G A 1977 Effect of prior stimulation on vibrotactile thresholds *Sens. Process.* **1** 292–300

Whitsel B L, Kelly E F, Quibrera M, Tommerdahl M, Li Y, Favorov O V, Xu M and Metz C B 2003 Time-dependence of SI RA neuron response to cutaneous flutter stimulation *Somatosens. Mot. Res.* **20** 45–69