Experimental Brain Research (2021) 239:279–288
https://doi.org/10.1007/s00221-020-05910-y

RESEARCH ARTICLE

Perceptual amplification following sustained attention: implications for hypervigilance

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Received: 17 March 2020 / Accepted: 20 August 2020 / Published online: 5 November 2020

Abstract

It is known that attending to a cutaneous stimulus briefly increases its subjective intensity. The purpose of the present study was to determine whether an extended period of attention would produce a longer-lasting perceptual amplification. Eighty subjects were assigned alternately to experimental and control groups. Members of the two groups received identical series of tactile stimuli (near-threshold von Frey filaments applied to the forearm), but those in the experimental group carried out a two-interval forced-choice detection task that required attention to the filaments, while subjects in the control group attended instead to a video game. After this initial phase, all subjects gave magnitude estimates of the intensity of a wide range of von Frey filaments. The experimental group gave estimates 42% greater than those of the control group, both for filaments used in the initial phase, and others not presented previously; the perceptual amplification did not, however, transfer to a different type of pressure stimulus, a 5 mm-diameter rod applied to the skin. The aftereffect of sustained attention lasted for at least 15 min. This phenomenon, demonstrated in normal subjects, may have implications for the hypervigilance of some chronic pain patients, which is characterized by both heightened attention to pain and long-lasting perceptual amplification of noxious stimuli.

Keywords Aftereffect · Attention · Hypervigilance · Magnitude estimation · Perceptual amplification · Tactile stimulation

Introduction

William James (1908, pp. 425–426) noted that "Most people would say that a sensation attended to becomes stronger than it otherwise would be." But he cautiously added, "This point is, however, not quite plain, and has occasioned some discussion…The subject is one which would well repay exact experiment, if methods could be devised."

James's call for "exact experiment" has been answered in recent decades, by psychologists and neuroscientists who experimentally manipulate the attention paid to stimuli, and then measure the resulting sensory experiences. For example, this approach has been used in research on the visual system, to show that attention alters stimulus appearance by increasing perceived contrast (Carrasco et al. 2004) and in other ways (see reviews by Carrasco 2011; Carrasco and Barbot 2019).

In the somesthetic modality, it has been shown that the perception of painful stimuli can be transiently modified by short-term experimental manipulations of attention (Miron et al. 1989; Villemure et al. 2003). Discrimination and detection of innocuous cutaneous stimuli are also transiently affected by attention under some experimental conditions (Bushnell et al. 1985; Post and Chapman 1991; Sathian and Burton 1991; Whang et al. 1991).

The recent finding that tactile frequency discrimination is better in musicians than in non-musicians (Sharp et al. 2019) suggests that attention over a long period of time may produce more enduring changes in somesthesis. This discovery is consistent with the classical finding (Recanzone et al. 1992) that frequency discrimination in owl monkeys is improved by extended training. Similar changes are found in a variety of sensory contexts, and are associated with a set of physiological (largely cortical) processes that are collectively referred to as plasticity (for recent review, see LeMessurier and Feldman 2018).

Communicated by Melvyn A. Goodale.

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Perceptual amplification in hypervigilance

Attention may also influence the sensory experiences of people with pain hypervigilance. Hypervigilance has been an important concept in the psychology of pain since it was introduced by Chapman (1978). He reported, based on clinical observation, that some pain patients "develop perceptual habits of vigilance for somatic distress signals," and described such individuals as somatically hypervigilant. There is now considerable support for the view that because pain strongly attracts our attention (Eccleston and Crombez 1999), and because chronic pain patients have pain that is constant or recurring, their close attention to noxious or threatening stimuli can become habitual (González et al. 2010; McCracken 1997; McDermid et al. 1996; Vlaeyen and Linton 2000; but see Van Damme et al. 2015).

Rollman and Lautenbacher (1993) broadened the concept of hypervigilance by showing that hypervigilant pain patients are on average more sensitive to noxious cutaneous stimulation than healthy controls. Moreover, McDermid et al. (1996) found that this increased sensitivity is not restricted to cutaneous stimuli, but extends to unpleasantly loud sounds as well. These findings led McDermid et al. to propose the Generalized Hypervigilance Hypothesis, according to which hypervigilance is a perceptual style that involves a broad-based amplification of aversive sensations.

The measure of perceptual amplification in these studies was a reduction in the threshold of pain or unpleasantness. Hollins et al. (2009) subsequently showed that perceptual amplification in hypervigilant pain patients also manifests itself as an increase in the perceived intensity of suprathreshold cutaneous and (to a lesser extent) auditory stimuli, compared to ratings by healthy control participants. The stimuli in their study covered a wide range of intensities, from low, innocuous levels to higher levels that were markedly aversive. Surprisingly, even pressures so weak that subjects did not regard them as unpleasant were perceptually amplified, perhaps as a result of generalization. Similar results were reported by Geisser et al. (2008).

Does attention cause perceptual amplification?

A central question, not yet resolved, is whether attentional processes are sufficient to induce the type of widespread perceptual amplification that is characteristic of hypervigilant chronic pain patients. It is difficult to evaluate this possibility in patients themselves, since there may be, in some cases, disease-specific physiological abnormalities that are contributing to the increased painfulness of noxious stimuli, independent of any effects of attention. In addition, attempts to induce additional amplification in someone who is already hypervigilant could be hampered by a ceiling effect.

An alternative approach would be to determine whether it is possible, by experimentally manipulating attention in a non-clinical sample, to produce an increase in sensory intensity that outlasts the conditions that induced it. To be considered analogous to perceptual amplification in hypervigilant individuals, such an increase should show three characteristics.

Duration

Hypervigilance and its associated perceptual amplification continue even when the patient's clinical pain—presumably a key inducing stimulus—is in temporary remission (Hollins et al. 2009; McDermid et al. 1996). If experimentally induced perceptual amplification in pain-free subjects is a related phenomenon, it too should extend beyond the period of its induction.

Innocuous induction

Perceptual amplification in chronic pain patients is associated with habitual attention to noxious or threatening stimuli, but it is not clear that the aversiveness of these stimuli is essential for the establishment of amplification. If sustained attention per se (rather than the nature of the attended stimulus) is the key requirement, then it ought to be possible to produce extended perceptual amplification in pain-free subjects using innocuous stimuli.

Generalization

If sensory changes induced in pain-free individuals are analogous to those associated with hypervigilance, they should generalize to stimuli other than the initially attended ones, just as occurs in chronic pain patients (McDermid et al. 1996).

In an earlier study in our lab using this approach (Hollins and Walters 2016), some subjects attended to a variety of innocuous bodily sensations, while others attended to visual and auditory stimuli instead. Later, both groups rated the intensity and unpleasantness of cutaneous pressure. The hypothesis tested was that the initial period of sustained attention to somesthetic sensations would modify the perception of subsequent test stimuli. An effect of inducing condition was found, but was difficult to interpret because of the variety of inducing stimuli used.

The present study

The present study was an examination of whether a long (approximately 50 min) period of nearly continuous attention to innocuous tactile stimuli of a single type (von Frey filaments, VFFs) can induce subsequent perceptual amplification in healthy pain-free subjects. We used a between-group manipulation of attention, rather than a within-group design in which different attentional conditions are interspersed.

We directed the attention of some participants toward, and others away from, the tactile stimuli by means of attention-demanding tasks lasting approximately 50 min. All subjects received the same amount of VFF stimulation, but members of the experimental group were required to report detection of these stimuli, while members of the control group played a fast-paced video game instead. Later, both groups rated the subjective intensity of a range of VFFs and other pressure stimuli. The question of interest was whether subjective ratings of the VFFs would be higher in the experimental group, and if so, whether this change would transfer to other pressure stimuli. Such findings would indicate that an extended period of attention is able to produce, in pain-free subjects, perceptual amplification resembling that observed in hypervigilant pain patients. In contrast, negative results would suggest that long-lasting perceptual amplification is not an inevitable result of sustained attention, or only occurs in clinically hypervigilant individuals.

Methods

Participants

There were 80 participants, students in introductory psychology classes who volunteered online and received research credit for participating. Exclusion criteria were: a chronic pain disorder, diabetes, or neurological impairment; or nerve damage, a history of surgery, or a current injury (such as a cut or bruise) in the right forearm. In addition, participants were required to be between 18 and 25 years of age. All aspects of the study were approved by the Institutional Review Board of the University of North Carolina at Chapel Hill.

Subjects were assigned to one of two groups, based on the order in which they were enrolled in the study. Odd-numbered subjects were assigned to the experimental group, even-numbered subjects to the control group.

After giving written informed consent, all subjects completed brief questionnaires concerning demographics and current pain. Responses showed that their ages ranged from 18 to 25, with an average of 19.0 years (SD 1.1); the mean ages of the experimental and control groups were statistically equivalent, $t(78) = 0.801$, $p = 0.425$. Fifty-eight participants (72.5%) were female, a percentage that did not differ significantly between groups, $X^2(1) = 1.00$, $p = 0.317$.

Any pain experienced over the previous 2 weeks was rated, on a 0–100 scale, as averaging 11.28 (SD = 10.78) in intensity and 10.51 (SD = 10.39) in unpleasantness; pain "right now" was rated as averaging 3.96 (SD = 4.01) in intensity and 4.68 (SD = 4.73) in unpleasantness. Independent-samples t tests showed that the experimental and control groups did not differ significantly on any of these measures (all $p > 0.6$).

Experimental procedures

The experiment consisted of three phases. Phase 1 was the experimental manipulation. The effects of that manipulation were measured in Phases 2 and 3.

Phase 1

Regardless of group, the subject sat at a table, and extended the right hand and forearm under a black curtain that prevented sight of the tactile stimuli. On each of a series of 100 trials, the volar surface of the subject's forearm, about midway between wrist and elbow, was stimulated with a von Frey filament (Aesthesio Precision Tactile Sensory Evaluators©, DanMicGlobal, San Jose, CA). Each filament delivered a specific normal force to the skin; forces available in our 20-filament set ranged from 8 mg to 300 g, in roughly logarithmic steps.

For subjects in the experimental group, the filaments constituted the stimuli in a two-interval forced-choice (2IFC) detection task (Gescheider 1997). On each trial, a filament was presented in one of two 1-s test periods, separated by a 2-s interval. Indicator lights, presented on a tablet computer (Lenovo ThinkPad© X60, 12-inch screen) that rested on the table and was positioned approximately 30° to the left of the subject's midline, marked the occurrence of the test periods and the response period, which immediately followed the second test period. The subject responded by saying "A" or "B" to indicate whether he/she thought the filament had been presented in the first or second test period, respectively. The subject was told immediately after each response whether it was correct or incorrect. Whether the stimulus occurred in the first or second test period of the trial was determined randomly.

Trials were grouped into blocks of 4, with the same filament (i.e., the same force) used on all four trials in a block. At the end of each block, the number of trials on which the subject had answered correctly was noted, and used to determine the stimulus force to be employed in the next block, in accordance with a tracking algorithm. If the subject guessed correctly on all four trials in a block, a slightly finer (i.e., lower force) VFF was employed in the next block; if the subject responded correctly on zero, one, or two trials in the block, a slightly thicker VFF was used in the next block; and if the subject was correct on three of the four trials, the same VFF was used again in the next block. In this way, the force employed gradually approached, and then hovered about, a level that elicited 75% correct responding—i.e., detection threshold. Testing always began with a filament that exerted a force of 1400 mg, an easily detectable stimulus.

A yoked-control design was used: each subject in the control group received exactly the same series of tactile stimuli as the immediately preceding experimental subject. For example, subject 2 received the same stimuli, in the same order, as subject 1; subject 4 received the same stimuli as subject 3; and so on. This was done to ensure that any differences between groups observed in Phases 2 and 3 could not be due to differences in tactile stimulation.

However, subjects in the control group were not asked to respond in any way to the tactile stimuli, and in fact were told they could ignore them. Their task was, instead, to play a video game displayed on the tablet screen. In this online game, *Fishy!* (XGen Studios; http://www.xgenstudios.com/play/fishy), the subject's avatar was a fish that sought to eat smaller fishes while escaping from larger ones. Subjects controlled the position of the avatar with the up, down, left, and right keys on the computer keyboard, using their left hand. A round of the game ended when the avatar was consumed by a larger fish, and the user was given his/her score for that round. Scores were a function of the number and types of fish consumed by the avatar. Subjects were instructed to call out their score at the end of each round, and to immediately begin another round.

Phase 2

Experimental and control subjects had different experiences in Phase 1 (the experimental manipulation), but they were treated identically for the remainder of the study. In Phase 2, they were again stimulated with von Frey filaments, but were now asked to give magnitude estimates of the sensation intensity produced by the filament on each trial. All responses were given vocally.

In preparation for this task, they were trained in free (i.e., no modulus) magnitude estimation by being asked to magnitude estimate the length of lines drawn on paper by the experimenter. It was explained to the subjects that they could use any nonnegative numbers—integers, fractions, or decimals—that represented the apparent length of each line, with the constraint that the numbers should be proportional to perceived line length. In other words, if one line looked twice as long as another, it should be given a magnitude estimate twice as great. To demonstrate to the subject that the range of numbers that could be used was unbounded, the experimenter drew at least one line short enough to elicit a rating less than 1, and at least one line long enough to elicit a rating greater than 10.

With this preliminary training completed, subjects again extended their right hand and forearm under the curtain, as in Phase 1, and magnitude estimation of the tactile stimuli began. On each trial, 1 of 11 VFFs, spanning the range from 600 mg to 60 g, was presented to the volar surface of the forearm, about midway between the wrist and the elbow. The location at which the filament was presented was varied slightly from trial to trial to avoid repeated stimulation of the same skin site. The 11 filaments were presented once, in random order (series 1); then all were presented a second time in a different random order (series 2).

Phase 3

The purpose of this final phase of the experiment was to determine whether the experimental manipulation carried out in Phase 1 would affect perception of tactile stimuli differing markedly from von Frey filaments. These stimuli were pressures applied with the flat circular tip of a plastic rod, 5 mm in diameter, that rested on the volar surface of the forearm approximately midway between wrist and elbow. Forces ranging from 77 to 1077 g were delivered by adding weights to scaffolding supported by the rod. On each trial, the stimulus was gently lowered onto the skin, left in place for 15 s, and then raised off the skin. Stimulus location was varied somewhat from trial to trial to avoid adaptation or sensitization. This apparatus and method of stimulus presentation are identical to those used in an earlier study from our lab (Hollins et al. 2009).

Instead of giving free magnitude estimates, subjects rated the perceived intensity of each pressure stimulus on a scale from 0 (no sensation) to 100 (the most intense sensation imaginable). They then classified each stimulus as painful, unpleasant but not painful, or neutral (i.e., neither pleasant nor unpleasant). Finally, they rated the unpleasantness of each stimulus on a scale from 0 (not at all unpleasant) to 100 (the most unpleasant sensation imaginable).

Questionnaires

The main question addressed by this study is whether perceptual amplification can occur following a period of sustained attention, without requiring either painful stimulation, or the already-present hypervigilance found in many chronic pain patients. Since our experimental procedures were narrowly focused on attention to (or distraction from) innocuous tactile stimuli, we did not expect these procedures to have an impact on broader psychological characteristics such as catastrophizing or affect, or to produce an overall state of hypervigilance. Indeed, it would have been concerning if heightened attention to the VFFs had produced such effects.

To rule out this possibility, we administered several widely used psychometric tests to measure state anxiety (the State portion of the State/Trait Anxiety Inventory: Spielberger et al. 1983), catastrophizing (Pain Catastrophizing Scale: Sullivan et al. 1995), and mood (Positive and Negative Affect Scales: Watson et al. 1988). We measured a tendency toward hypervigilance with three psychometric instruments. One of these was the Pennebaker Inventory of Limbic Languidness (the PILL: Pennebaker 1982), an indirect measure used in our earlier research (Hollins et al. 2009; see also McDermid et al. 1996). This questionnaire asks respondents how often they experience various unpleasant bodily symptoms/sensations, such as sore feet or a runny nose. Scores are assumed to reflect attention to and recollection of symptoms, rather than their mere occurrence. We also administered two questionnaires that provide direct measures of hypervigilance: the Body Vigilance Scale (Schmidt et al. 1997) and the Pain and Vigilance Awareness Questionnaire (McCracken 1997). The former asks respondents how much attention they paid during the previous week to internal bodily sensations, especially to unpleasant ones such as heart palpitations or nausea. The latter asks only about attention to painful sensations.

Data analysis

Phase 1

To examine threshold tracking data in the experimental group, VFF forces were converted to logarithmic form, and the average log force used in each four-trial block was then determined. The average log force at which performance stabilized served as an estimate of threshold.

Phase 2

Each subject's estimates of sensation intensity were converted to logarithmic form, and the resulting values subjected to an 11 (force) × 2 (series) × 2 (group) mixed-model ANOVA. The question of greatest interest was whether there was a main effect of group, i.e., an effect of the experimental manipulation. For all statistical tests, a two-tailed alpha level of 0.05 was used.

Phase 3

Sensation intensity values for the weighted rods were converted to logarithmic form and subjected to an 11 (force) × 2 (group) mixed-model ANOVA; an equivalent ANOVA was carried out for values of stimulus unpleasantness. To examine classification responses, we tallied for each subject the number of trials on which a stimulus was called painful, and then compared the distribution of these tallies in the experimental and control groups using a Mann–Whitney *U* test. A similar test was carried out on tallies of painful and unpleasant-but-not-painful responses combined.

Results

Phase 1: Experimental manipulation

Pressure detection

Forced-choice testing of VFF detection always began with a filament that exerted a force of 1400 mg, a value well above detection threshold (see Fig. 1). All members of the experimental group responded correctly on all four trials of block 1, so that (in accordance with the tracking algorithm) a slightly lower force was applied in block 2. As shown in Fig. 1, force continued to decline, but more and more gradually, over the course of 10–15 blocks, after which it fluctuated about a level of about 65 mg (1.8 log mg). This is comparable to the widely accepted values of VFF detection threshold on the forearm given by Weinstein (1968).

Distraction task

As a measure of performance on the distraction task (video game), we calculated for each control-group subject the sum of the scores for individual rounds provided by the game itself. Total scores were integers ranging from 1950 to 88,884, in a positively skewed distribution. Since high

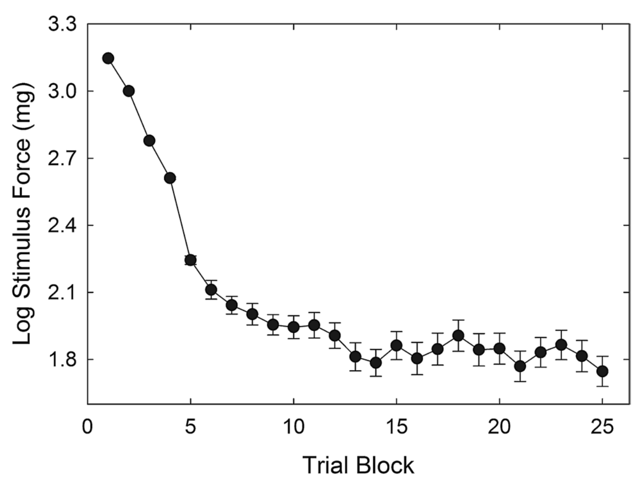

Fig. 1 Average log force exerted by the von Frey filament used in each four-trial block of the pressure detection task, for subjects in the experimental group ($N = 40$). The logarithm of force is plotted because filament forces were spaced at roughly equal logarithmic intervals. Error bars show ± 1 SEM. The standard error is zero for the first block because all participants started with the same force, 1400 mg (3.15 log mg)

game scores may in part indicate effective distraction from the VFFs in Phase 1, we investigated the possibility that they were associated with low VFF intensity ratings in Phase 2, using Spearman's rho, a nonparametric measure of correlation; it was not significant, $r_s(40) = 0.102$, $p = 0.530$.

Phase 2: Subjective scaling of VFFs

Following their training in free magnitude estimation of line lengths, participants rated the intensity of the sensation elicited by each of 11 different VFFs, presented twice in different random orders (series 1 and series 2). The 1760 individual ratings ranged from 0 (3.6% of the total) to 60. As is customary with magnitude estimation data, the logarithm of each rating was taken; because the log of zero is undefined, ratings of 0 were replaced with 0.025 (half the smallest non-zero rating given by any subject) prior to the log transformation.

A mixed-model 11 (force) × 2 (series) × 2 (group) ANOVA showed that the main effect of force was highly significant, $F(10, 780) = 276.3$, $p < 0.001$, with sensation intensity rising steadily as force increased. The effect of group was also significant, $F(1, 78) = 4.62$, $p = 0.035$, with sensation intensity being about 42% (= 0.15 log unit) greater in the experimental group than in the control group.

The interaction of force and group was not significant [$F(10, 780) = 0.484$, $p = 0.901$], indicating that the log difference between the groups in ratings was comparable across all levels of force. This can be seen in Fig. 2, where each point is the average log response to a given stimulus, for the 40 subjects in the experimental (filled symbols) and control (open symbols) groups.

In addition, the effect of series was significant, $F(1, 78) = 21.39$, $p < 0.001$, reflecting the fact that log sensation intensity declined from series 1 ($M = 3.20$, $SD = 0.320$) to series 2 ($M = 3.12$, $SD = 0.342$), perhaps as a result of cumulative peripheral adaptation to the tactile stimuli in both groups. Importantly, the interaction of series and group was not significant, $F(1, 78) = 0.464$, $p = 0.498$; there is thus no evidence that the aftereffect of the experimental manipulation declined from series 1 to series 2. Finally, the analysis revealed an interaction between series and force, $F(10, 780) = 3.04$, $p = 0.001$, with log sensation intensity declining more at low than at high force levels between series. The three-way interaction was not significant.

There was a suggestion in the data that attention produces greater perceptual amplification in females (47%) than in males (24%). However, the number of male participants (9 in the experimental group and 13 in the control group) was too small for conclusions about possible sex differences to be drawn.

Phase 3: Subjective scaling of weighted rod

Phase 3 of the experiment addressed the question of whether the experimental and control groups would differ in their perception of another type of pressure stimulus: a weighted rod, applied end-on to the skin. Although activating the same submodality (pressure) at the same location (forearm) as the VFFs, the two types of stimulation were subjectively distinctive because of differences in stimulus geometry, total force, time course, and other properties.

Perceived intensity of these stimuli is plotted as a function of force in Fig. 3. It can be seen that the results for the experimental and control groups are virtually identical.

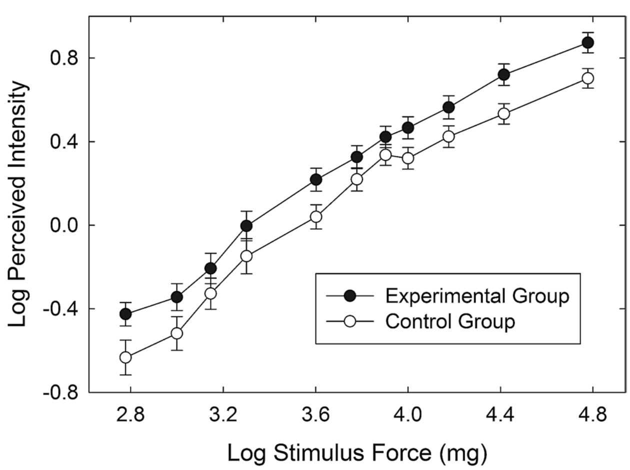

Fig. 2 Log perceived intensity of suprathreshold von Frey filaments. Each point is the average log magnitude estimate of 40 subjects in either the experimental group (filled symbols) or the control group (open symbols). Error bars show ± 1 SEM

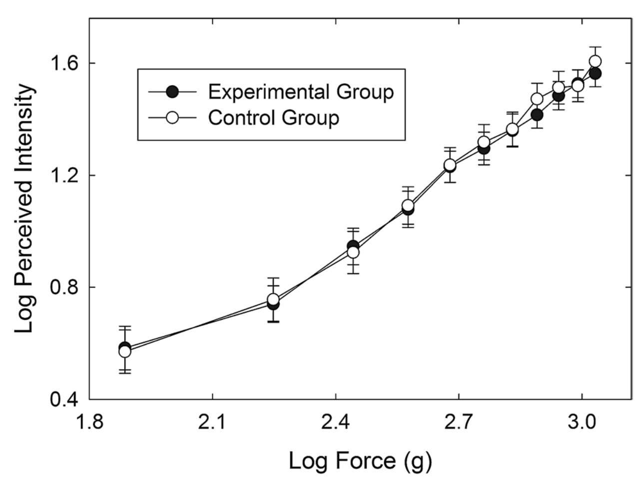

Fig. 3 Log perceived intensity of the weighted rod as a function of log force, for the experimental (filled symbols) and control (open symbols) groups. Each force was presented once to each subject. Error bars show ± 1 SEM

An 11 (force) × 2 (group) mixed model ANOVA confirmed that while the effect of force was highly significant, $F(10, 780) = 183.1$, $p < 0.001$, neither the main effect of group [$F(1, 78) = 0.034$, $p = 0.854$] nor the interaction [$F(10, 780) = 0.230$, $p = 0.993$] was significant.

Subjects also classified the weighted rod stimulus as painful, unpleasant but not painful, or neutral (i.e., neither pleasant nor unpleasant) on each trial. The percentage of subjects who found the stimulus painful was negligible at low force levels, but rose substantially at the highest force levels (Fig. 4). The percentage of subjects who found the rod either painful or unpleasant was much higher, approaching 100% at the highest force levels.

To compare the classification responses of the two groups, we first tallied, across force levels, the number of times (out of a possible 11) each subject indicated that a stimulus was painful. Since classification response tallies are at an ordinal level of measurement, we used a nonparametric test, the Mann–Whitney U test, to analyze them. The across-subject medians of these tallies were similar in the experimental group (Mdn = 0.5) and the control group (Mdn = 1), and the distributions were not significantly different, $U = 971.0$, $p = 0.086$. Next, we tallied for each subject the combined number of painful and unpleasant responses: Median values were identical for the experimental and control groups (Mdn = 7), and the difference between the distributions was not significant, $U = 804.5$, $p = 0.965$. The classification data thus do not provide evidence for an effect of the experimental manipulation on the affective quality of the weighted rod stimulus.

Finally, subjects rated the unpleasantness of the weighted rod on a 0–100 scale (Fig. 5). These ratings address the same

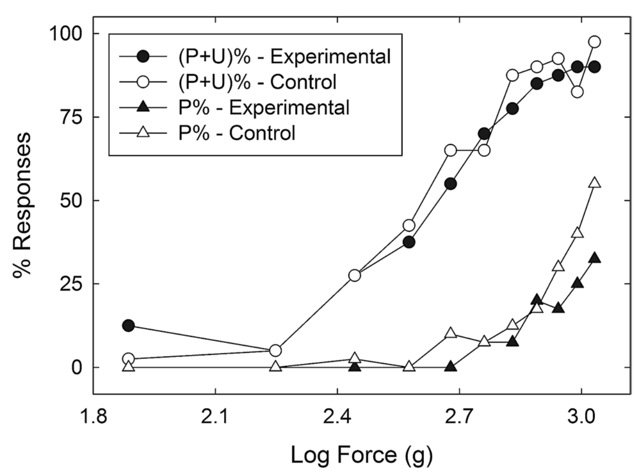

Fig. 4 Classification responses of the weighted rod, as a function of stimulus force, for the experimental (filled symbols) and control groups (unfilled symbols). Triangles show the percentage of subjects who found a stimulus painful ($P\%$); circles show the percentage who found it either painful or unpleasant, $(P + U)\%$

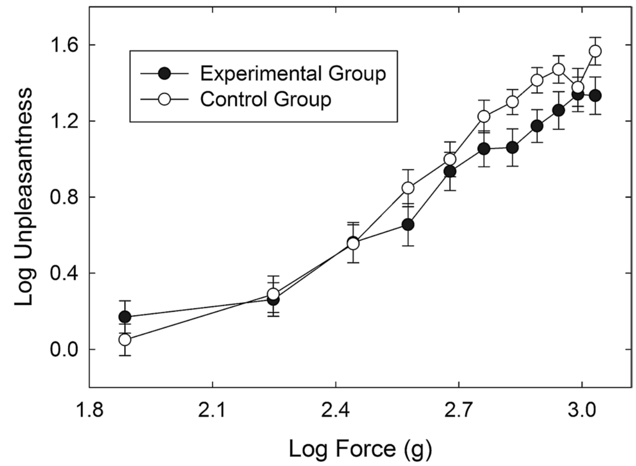

Fig. 5 Log unpleasantness of the weighted rod as a function of log force, for the experimental (filled symbols) and control (open symbols) groups. Error bars show ± 1 SEM

question as the classification responses—i.e., whether the experimental manipulation influenced the affective quality of a novel stimulus—but in a more parametric way. An 11 (force) × 2 (group) mixed-model ANOVA showed that the effect of force on unpleasantness was highly significant [$F(10, 780) = 127.3$, $p < 0.001$], but the main effect of group was not, $F(1, 78) = 1.32$, $p = 0.254$. However, the interaction term was significant [$F(10, 780) = 2.23$, $p = 0.015$], reflecting the fact that at higher levels of force, the rod was judged more unpleasant by the control group than by the experimental group.

Questionnaires

For each post-experiment questionnaire, scores of the experimental and control groups were compared using a *t* test. In no case was there a significant difference between groups (all $p > 0.1$). There is thus no evidence that the experimental procedures differentially influenced the state anxiety, catastrophizing, or positive or negative affect of participants, or their tendency toward hypervigilance.

Discussion

Sustained attention produces lingering perceptual amplification

The primary purpose of this study was to determine whether sustained attention to innocuous tactile stimuli would produce an increase in their subjective intensity outlasting the period of the experimental manipulation. To answer this question, we assigned healthy, pain-free subjects alternately to two groups. In Phase 1 of the study, the experimental group participated in a two-interval forced choice (2IFC) detection task that extended over 100 trials. The stimuli were thin von Frey filaments (1400 mg and below) that evoke weak tactile sensations. Subjects' excellent performance (Fig. 1) shows that, as instructed, they were attending closely to the task: They were able to achieve, and maintain, thresholds equivalent to canonical values in the literature (Weinstein 1968). Subjects in the control group did not attempt to detect the tactile stimuli; instead, they played an attention-demanding video game.

To ensure that subjects in the two groups were treated identically except for the attentional manipulation, a yoked-control design was used. Each subject in the control group was "yoked" to the immediately preceding member of the experimental group, receiving an identical series of tactile stimuli. A difference in results between the groups could thus not be attributed to any differences in tactile stimulation.

Subsequent to the experimental manipulation, all participants were treated identically. In Phase 2 of the experiment, they gave free magnitude estimates of sensation intensity for VFFs spanning a 2-log-unit range, extending from weakly perceptible to marginally painful. These filaments were, on average, judged 42% stronger by members of the experimental group than by members of the control group (Fig. 2). The most plausible interpretation of this result is that sustained attention to tactile stimuli causes an increase in their subjective intensity when they are later presented again.

It might be argued that the aftereffect resulted, instead, from a drop in the perceived intensity of the test stimuli for members of the control group. We consider this unlikely, since Kalisch et al. (2007) showed that 3 h of passive stimulation (irregular tapping) of the fingers had no effect on VFF threshold. However, further research is needed to conclusively settle the question.

The design of the present study did not enable us to parametrically determine the time course of the aftereffect, but the results suggest a lower bound to its duration, on the order of minutes. The experimental manipulation (Phase 1) took approximately 50 min, and an interval of about 5 min separated the end of Phase 1 from the start of testing (Phase 2) in which all subjects gave magnitude estimates of the subjective intensities of VFFs. The group difference in those estimates indicates that the effect of the experimental manipulation lasted more than 5 min.

Moreover, two series of VFF stimuli were delivered during testing, and perceptual amplification in the experimental group did not decline from series 1 to series 2. Each series took approximately 5 min, so the lack of a decline between series implies that the aftereffect of sustained attention lasts for at least 15 min, and probably longer. Further research is needed to systematically determine the duration and time course of the aftereffect. However, it is interesting to note that some visual aftereffects can last for days (Riggs et al. 1974).

Does the aftereffect of sustained attention generalize?

The geometric difference in magnitude estimates (0.15 log unit) of the VFFs was comparable for low-intensity stimuli that had been presented in Phase 1 (i.e., the three leftmost values in Fig. 2) and for stronger stimuli that were new to the subjects. This equivalence across the stimulus range shows that perceptual amplification was not limited to stimuli used earlier; instead, it generalized to an entire *class* of stimuli. Whether this class was von Frey filaments, pressure stimuli more generally, or all tactile stimuli, is a question that was addressed by Phase 3 of the study.

The purpose of Phase 3 was to determine whether the perceptual amplification shown to occur in the experimental group for VFFs would extend to pressure stimuli of a different type applied to the same skin location: weighted rods differing from the VFFs in diameter, force, and presentation duration. We found that perceptual amplification did not occur with the weighted rods: Their perceived intensity was essentially identical in the experimental and control groups, a result suggesting that the perceptual amplification demonstrated in this study may be limited to the type of stimulus on which sustained attention was initially focused.

Implications for perceptual amplification in hypervigilance

Is the perceptual amplification demonstrated here in pain-free subjects analogous to that shown by hypervigilant pain patients, and therefore consistent with the possibility that sustained attention is its primary cause in the patients? If so, the present data should satisfy three criteria, as described in the Introduction.

First, the experimental perceptual amplification should outlast the brief perceptual changes produced by short-term attentional manipulations in earlier studies (Bushnell et al. 1985; Miron et al. 1989; Post and Chapman 1991; Sathian and Burton 1991; Villemure et al. 2003; Whang et al. 1991). The present results do satisfy this criterion: Perceptual amplification of VFFs continued to occur in the experimental group for at least 15 min after the attentional manipulation had ended.

Second, if sustained attention to any set of stimuli leads to their prolonged amplification, it should be possible to produce long-lasting experimental PA even with innocuous stimuli. The present results also satisfy this criterion, since the VFFs produced only very light tactile sensations, yet sustained attention to them produced the aftereffect.

Third, the perceptual amplification experienced by healthy pain-free subjects should generalize to related classes of stimuli. In the present study this possibility was tested by having subjects—after rating the VFFs—rate another type of pressure stimulus, the weighted rod. The third criterion was not satisfied: Perception of the weighted rod stimuli was not amplified in the experimental group. This result is in contrast to the finding (Hollins et al. 2009) that in hypervigilant pain patients, these same weighted rods were perceptually amplified.

However, the present data show that, at high force levels, the unpleasantness of the weighted rod was significantly lower in the experimental group than in the control group. This finding is opposite to what would be expected if an affective component of perceptual amplification were occurring; it suggests instead that sustained attention may have effects that are different, in both breadth and direction, on different perceptual dimensions (such as intensity and unpleasantness). Further research will be needed to elucidate this finding.

One possible explanation for the fact that sustained attention did not produce, in our pain-free subjects, perceptual amplification fully comparable to that shown (Hollins et al. 2009) by hypervigilant pain patients is that people with hypervigilance have a history of sustained attention to wide variety of unpleasant or potentially threatening stimuli, including stimuli similar to the weighted rod. If the weighted rod stimuli, while formally novel, were similar to stimuli attended to earlier by patients in the Hollins et al. study, this could explain why those patients experienced them as intensified. Additional research—perhaps involving sustained attention to markedly novel stimuli by both hypervigilant and non-hypervigilant individuals—is needed to evaluate this possibility.

In any case, the present results have implications beyond those dealing with hypervigilance. For example, the fact that sustained attention to a set of stimuli can produce a prolonged increase in their perceived intensity may complicate interpretation of studies in which participants are asked to distinguish familiar stimuli from unfamiliar ones. Further research is needed to determine how long the amplification persists, and with what time course it returns (in the absence of additional periods of sustained attention) to baseline.

Limitations of the study

The present study has two notable limitations. The first is that there were no baseline measurements of perceived VFF intensity, prior to the experimental manipulation. Baseline measurements were omitted so that subjects would be naive regarding the subjective experience of the filaments at the start of Phase 1. We considered this naiveté important, because preliminary measurements would have made the filaments salient to the subjects, possibly making it more difficult for those in the control group to ignore them during Phase 1. Furthermore, preliminary measurements might have triggered perceptual amplification of unknown duration in both groups, possibly leading to a ceiling effect for the experimental group in Phase 2. Nevertheless, it would be desirable to include baseline measurements in future studies, if this could be done without weakening the experimental manipulation. One possible approach would be to conduct baseline measurements in a separate session, several days earlier than the rest of the experiment.

The second limitation of the present study is that we cannot firmly establish whether the lack of perceptual amplification of the weighted rods was due to lack of transfer, or to a decline of perceptual amplification with the passage of time. The abrupt change in the pattern of results between Phases 2 and 3 is, we believe, more consistent with the former alternative, but the issue remains unsettled. A way to address it in future studies would be to counterbalance Phases 2 and 3.

Acknowledgements The authors are grateful to Noah Greifer for statistical advice. This study was supported by a Lindquist Award from the UNC College of Arts and Sciences.

Author contributions Both authors contributed to the conception and design of the study, to preparation of materials, and to data analysis. Data collection was carried out by LA. The first draft of the manuscript was written by MH; both authors commented on drafts, and read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest The authors have no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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