Know your movements

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Know Your Movements: Poorer Proprioceptive Accuracy is Associated With Overprotective Avoidance Behavior

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Abstract: **Pain-related avoidance of movements that are actually safe (ie, overprotective behavior) plays a key role in chronic pain disability. Avoidance is reinforced through operant learning: after learning that a certain movement elicits pain, movements that prevent pain are more likely to be performed. Proprioceptive accuracy importantly contributes to motor learning and memory. Interestingly, reduced accuracy has been documented in various chronic pain conditions, prompting the question whether this relates to avoidance becoming excessive. Using robotic arm-reaching movements, we tested the hypothesis that poor proprioceptive accuracy is associated with excessive pain-related avoidance in pain-free participants. Participants first performed a task to assess proprioceptive accuracy, followed by an operant avoidance training during which a pain stimulus was presented when they performed one movement trajectory, but not when they performed another trajectory. During a test phase, movements were no longer restricted to 2 trajectories, but participants were instructed to avoid pain. Unbeknownst to the participants, the pain stimulus was never presented during this phase. Results supported our hypothesis. Furthermore, exploratory analyses indicated a reduction in proprioceptive accuracy after avoidance learning, which was associated with excessive avoidance and higher trait fear of pain.**

Perspective: ***This study is the first to show that poorer proprioceptive accuracy is associated with excessive pain-related avoidance. This finding is especially relevant for chronic pain conditions, as reduced accuracy has been documented in these populations, and points toward the need for research on training accuracy to tackle excessive avoidance.***

Key Words: *proprioception, avoidance behavior, chronic pain, operant conditioning, robotic arm.*

Avoidance of pain-associated movements is an adaptive response to acute pain as it may protect against (further) injury. For example, if a shooting pain is experienced while bending the back, not repeating this movement can prevent exacerbating an injury. However, when injury is not, or no longer, present, avoidance may prevent learning that these movements are actually safe. Moreover, avoidance can spread toward movements similar to a pain-associated one, regardless of whether these were experienced with pain (ie, generalization;).[10] This again is an adaptive mechanism that may become maladaptive when applied excessively to safe movements (ie, overgeneralization). Such overprotective behavior may instigate a self-sustaining cycle of disengagement from harmless daily and valued activities (eg, household chores, social activities), contributing to chronic pain disability (fear-avoidance model of pain).[4,19,37]

Pain-related avoidance of movements can be acquired through operant learning:[21] avoidance behaviors are reinforced by the omission of pain (among other factors),[17] making them more likely to occur in the future.

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Proprioceptive accuracy plays a key role in this, as accurate perception of motion and position of the body and body segments in space contributes to motor learning and memory.[26] Interestingly, reduced proprioceptive accuracy has been observed in a range of chronic pain conditions,[15,16,31,34] suggesting this may play a role in avoidance becoming excessive, thus contributing to disability. Not being able to accurately perceive and encode technically safe movements may lead to these movements being avoided as well, leading to a reduced movement repertoire. Yet to date, research investigating the relationship between proprioception and avoidance is lacking.

Support for a potential link comes from conditioning studies in the field of anxiety disorders. These studies show that, after pairing a (visual) stimulus with an aversive outcome, the spreading of fear responses toward perceptually similar stimuli that were never paired with this outcome (ie, fear generalization) is modulated by perceptual accuracy.[32,39,40] Specifically, fear generalization is negatively related to the degree to which one stimulus can be differentiated from another.[6,25] Moreover, evidence suggests that aversive conditioning itself has the potential to decrease perceptual accuracy.[18,29,41] From a predictive processing perspective, this may be due to a "better safe than sorry" processing strategy. This perspective posits that the brain generates a model of internal and external environments by comparing sensory input to predicted input. It could be that reduced proprioceptive accuracy is a result of increased weighting of the affective-motivational aspects of input at the expense of detailed sensory-discriminative input.[35]

As avoidance is a key characteristic of fear,[17] it can be expected that perceptual accuracy modulates avoidance as well. However, whether this is true, and whether proprioceptive accuracy specifically can play a modulating role, remains to be investigated. The current study tested the hypothesis that poor proprioceptive accuracy is associated with overprotective avoidance behavior, using the Dynamic Movement Reproduction (DMR) task —a recently developed measure for proprioceptive accuracy[36]—and an operant avoidance task consisting of robotic arm-reaching movements. During the avoidance training, one movement trajectory was paired with a pain stimulus, while another was not. During the avoidance test, movements were no longer limited to 2 trajectories, but participants were instructed to avoid the pain stimulus. We expected participants with poorer proprioceptive accuracy to show excessive avoidance in terms of increased deviation from the avoidance trajectory, away from the pain-associated trajectory.

Methods

Ethical Approval and Preregistration

The experimental protocol was approved by the Ethics Review Committee Psychology and Neuroscience of Maastricht University (registration number: 185 09 11 2017 S9). Before starting the experiment, all participants read an information sheet, completed an exclusion criteria checklist, and provided written informed consent. Because this study was conducted during the SARS-CoV-2 pandemic, additional safety measures were used according to institutional guidelines (eg, both experimenter and participant wore facemasks, the experimenter wore gloves while attaching electrodes). The experimental protocol and analysis plan were registered prior to data collection at Open Science Framework (https://osf.io/erymf/?view_only=7b64a38469e04b1eb38f59d0e08bc43e).

Participants

A registered a priori power analysis using G*Power (Heinrich-Heine-Universität, Düsseldorf, Germany) for our main hypothesis (bivariate correlation) indicated a sample of 46 participants would allow .80 power to detect a medium correlation of .40, at .05 alpha error probability (2-tailed). We decided to test 48 participants to balance counterbalancing conditions. Participants were recruited using the research participation system of Maastricht University (Sona), advertisements distributed around the university campus, and through social media. Seven participants were excluded during data preparation, resulting in a final sample size of 41 participants (11 male, 30 female, $M \pm SD$ [range] age = 24 $\pm$ 4 years [18−35]), allowing detection of a .42 correlation according to a sensitivity analysis with G*Power − using the same input as the a priori analysis. Participants received either 1 course credit or €7.5 in gift vouchers as a compensation. Exclusion criteria were chronic pain; analphabetism or diagnosed dyslexia; pregnancy; left-handedness; current/history of cardiovascular disease; current/history of psychiatric disorder (eg, clinical depression, panic/anxiety disorder); uncorrected problems with hearing or vision; having pain at the dominant hand, wrist, elbow or shoulder that may hinder performing the reaching task; presence of implanted electronic medical devices (eg, cardiac pacemaker); and presence of any other severe medical conditions. It should be noted that no information on race or ethnicity of participants was collected.

Apparatus and Software

Movements were performed using the HapticMaster (Motekforce Link, Amsterdam, the Netherlands; Fig 1), a 3 degrees-of-freedom force-controlled robotic arm that can be moved in all directions within a specific volume of space by exerting force on its handle, which is a sensor attached at the end of the arm. It allows horizontal movement with a depth of 40 cm, vertical movement with a height of 40 cm, and 60 degrees of rotation around its vertical axis with minimum radius 46 cm. Position is automatically logged along all 3 dimensions every 2 milli seconds, with a resolution of 10^{-4} cm. In the current task, height remained constant: movements were confined to a 2-dimensional horizontal plane. The experimental task was programmed in C#, using cross-platform game engine Unity 2017 (Unity Technologies, San

Figure 1. Experimental setup, reproduced with permission from Glogan, Gatzounis, Vandael, Franssen, Vlaeyen, Meulders.[9]

Francisco, CA), and was run on a Windows 10 Enterprise (Microsoft Corporation, Redmond, WA) 64-bit Intel Core desktop computer (Intel Corporation, Santa Clara, CA) with 8 GB RAM, CPU: i7-7700 at 3.600 GHz. A direct application programming interface (API) connection was used for communication between the computer and HapticMaster. The experimental task was presented on a 40-inch LCD screen (Samsung UE40ES5500; Samsung Group, Seoul, South Korea). Participants used a foot switch (USB Triple Foot Switch II; Scythe Co., Ltd., Tokyo, Japan) to navigate through instructions and answer questions.

A 2 milli seconds square-wave electrical stimulus was used as pain stimulus, which was delivered by a commercial constant current stimulator (DS7A; Digitimer, Welwyn Garden City, United Kingdom) through 2 reusable stainless steel disk electrodes (8 mm diameter with 30mm spacing; Digitimer, Welwyn Garden City, United Kingdom) filled with K-Y gel (Reckitt Benckiser, Slough, United Kingdom). The electrodes were placed on the triceps tendon of the right arm. The physical intensity of the stimulus was individually calibrated to be significantly painful and demanding some effort to tolerate.

Procedure

We employed a repeated measures design in which all participants performed the DMR task followed by the operant avoidance task. In both tasks, all movements were carried out in the same horizontal plane and were performed actively by participants, meaning that participants exerted force to move the HapticMaster. The experimental session took approximately 1 hour. After the experiment, participants completed a number of questionnaires.

Dynamic Movement Reproduction Task

Practice

Instructions on how to operate the HapticMaster and the task procedure were presented on-screen, which included movement direction and pattern shape (Fig 2). After reading these, participants wore a blindfold for the remainder

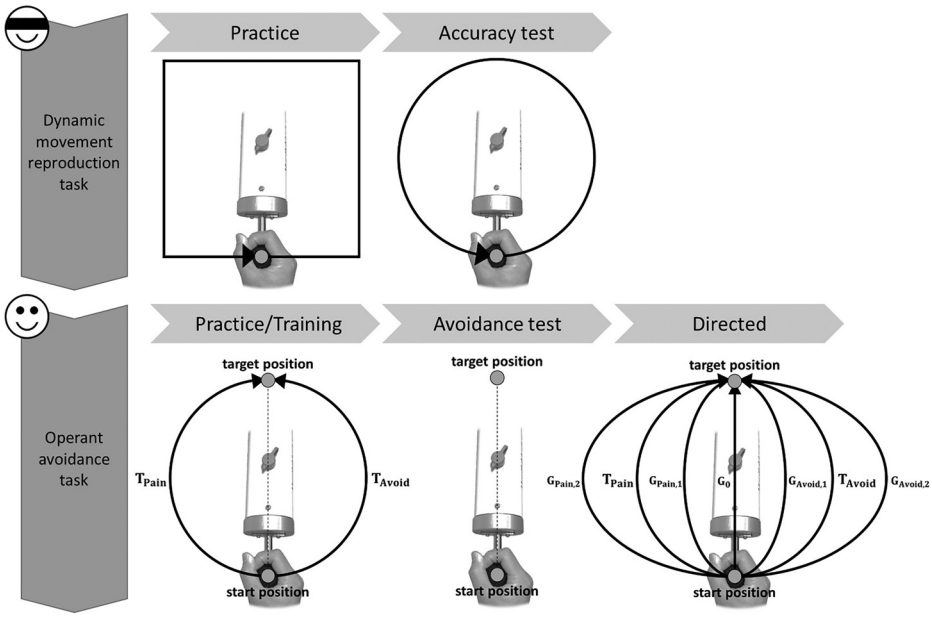

Figure 2. Movement trajectories presented during phases of the Dynamic Movement Reproduction (DMR) and operant avoidance tasks. Movement directions were counterbalanced. Emoji indicate whether participants wore a blindfold. During the operant avoidance task, 2 trajectories were presented during practice (no pain stimuli presented) and avoidance training. During the latter, one trajectory was paired with the pain stimulus (80% chance; T_{Pain}), while the pain stimulus could be avoided by performing the other trajectory (T_{Avoid}). The dotted line indicates the shortest trajectory (used as reference, see Primary outcome measures section), but was not available during practice and training. The entire horizontal movement plane was available during the avoidance test. Seven trajectories were presented in random order (1 per trial) during the directed phase: the shortest trajectory between start and target position (G_0), the pain-associated trajectory (T_{Pain}), the avoidance trajectory (T_{Avoid}), and a trajectory on each side of the training trajectories (ie, between the shortest trajectory and the training trajectories, $G_{Pain,1}$ and $G_{Avoid,1}$ respectively; on the outside of the training trajectories, $G_{Pain,2}$ and $G_{Avoid,2}$ respectively).

of the task, which is standard practice when assessing proprioceptive accuracy (eg,[2]). On each trial, the HapticMaster first restricted movement to a single trajectory, ie, the target movement. During all practice trials, this was a square with a side length of 16 cm, with the starting position always in the middle of the side closest to the participant. The movement direction (ie, clockwise or counterclockwise) was counterbalanced between participants (order based on pre-made list). A starting tone together with the automated audio message "*Start guided movement*" prompted participants to start moving. Movement in the wrong direction resulted in an error message and restart of the trial. After performing the target movement once, participants were instructed to reproduce this movement as accurately as possible. A starting tone together with the automated audio message "*Start free movement*" prompted participants to start moving. Participants indicated when they finished movement reproduction by saying "*Stop*," which prompted the experimenter to end the trial manually. An end tone was presented upon trial termination and the HapticMaster then moved to the starting position of the next trial. This phase consisted of 4 trials. The entire range of the robotic arm—within the horizontal plane—was available during reproduction. Six different starting positions within the horizontal plane were used in random order and no feedback regarding participants' performance was provided.

Accuracy Test

The procedure during the test phase was identical to the practice phase, except that the shape of the target movements was changed to a circle with a radius of 8 cm for all test trials. Again, 6 different starting positions within the horizontal plane were used in random order, which were always positioned on the point of the circle closest to the participant. This phase consisted of 6 trials.

Pain Calibration

To individually calibrate the intensity of the electrical stimulus, we followed a standard protocol (eg,[10]) in which participants received a series of stimuli of increasing intensity (starting at 1.00 mA). Participants rated each stimulus on a numerical scale ranging from 0 to 10, with 0 labeled as "*I feel nothing*"; 1 as "*I feel something, but this is not unpleasant; it is only a sensation*," 2 as "*the stimulus is not yet painful, but is beginning to be unpleasant*," 3 as "*the stimulus starts being painful*," and 10 as "*this is the worst pain I can imagine*. Participants were asked to select a stimulus they would describe as "*significantly painful and demanding some effort to tolerate*," corresponding to a 7 or 8 on the numerical pain scale.

Operant Avoidance Task

The operant avoidance task consisted of an arm-reaching task in which participants moved the handle of the HapticMaster from a start position to a target position. Note that these positions remained the same during the entire task. Participants no longer wore a blindfold, and contrary to previous operant avoidance tasks using the HapticMaster in our lab (eg,[10]), no on-screen visual feedback on movements was provided.

Practice

During this phase, the HapticMaster restricted movement along 2 trajectories to reach the target position, each consisting of half a circle (radius = 8 cm; identical to DMR task): one to the left of the middle line connecting start and target position (ie, clockwise), and one to the right (ie, counterclockwise; Fig 2). A starting tone together with the written message "*Start movement!*" prompted participants to start moving. When reaching the target, an end tone was presented together with the written message "*Target reached!*." The HapticMaster then returned to the start position and the next trial started. This phase consisted of 6 trials. On the first 2 trials, movement direction was instructed to guarantee that participants experienced both trajectories. For the remaining (4) trials, participants could freely choose which trajectory they performed. Note that only 2 trajectories were available during the entire phase. Participants also practiced providing anticipatory pain-expectancy and pain-related fear ratings for each trajectory; no pain stimuli were presented.

Avoidance Training

This phase was identical to the practice phase, except that participants could now freely choose between the 2 trajectories on all trials, and pain stimuli were presented. One movement trajectory was followed by the pain stimulus with 80% probability, while the other was never paired with the pain stimulus (avoidance movement; counterbalanced between participants; order based on pre-made list). The pain stimulus was triggered automatically when two-thirds of the movement trajectory was performed. Participants were not informed of these contingencies before starting the training. This phase consisted of 2 blocks of 12 trials. Participants provided anticipatory pain-expectancy and pain-related fear ratings at the start (trial 1 of block 1), middle (trial 12 of block 1), and end (trial 12 of block 2) of the phase.

Avoidance Test

The main difference in this phase was that movements were no longer restricted along 2 trajectories, meaning that participants were free to perform any movement —within the predefined horizontal plane—to reach the target position. However, they were explicitly instructed to avoid the pain stimulus. This phase consisted of 12 trials, and no pain stimuli or questions were presented. Participants were not informed of the change in contingencies before starting the test.

Directed Phase

During this phase, movements were restricted to 1 trajectory per trial. Seven trajectories were performed in random order: the shortest trajectory between start and target position (a straight line; G_0), the pain-associated trajectory (T_{Pain}), the avoidance trajectory (T_{Avoid}), and a trajectory on each side of these trajectories (ie, between the shortest trajectory and the training trajectories, $G_{Pain,1}$ and $G_{Avoid,1}$ respectively; on the outside of the training trajectories, $G_{Pain,2}$ and $G_{Avoid,2}$ respectively). Participants performed each of these trajectories once (ie, 7 trials) and provided retrospective pain-expectancy and pain-related fear ratings after each movement. No pain stimuli were presented, but participants were again not informed of this.

Primary Outcome Measures

Proprioceptive accuracy was operationalized as the absolute difference (in cm) between the target and the reproduced circular movement pattern (ie, difference between radiuses), averaged over the 6 test trials of the DMR task. Larger values reflect poorer accuracy. The reproduced radius was calculated using the coordinates of each performed movement, as logged by the HapticMaster, and the coordinates of the center of the target circle. This measure has shown good-to-excellent test-retest reliability.[36]

Anticipatory pain-expectancy and pain-related fear ratings were provided using the on-screen questions, "*To what extent do you expect an electrical stimulus when moving to the left/right?*" and "*How afraid are you to move to the left/right?*", which were answered using a Visual Analogue Scale ranging from 0 to 100 (0 = "*not at all*" and 100 = "*very much*").

Avoidance proportion was operationalized as the proportion of avoidance movements per block of the operant avoidance task, using the shortest trajectory – a straight line from start to target–as reference (ie, average orthogonal deviation from this line). On each trial, movements on the side of the avoidance trajectory were coded as avoidance movement; movements on the side of the pain-associated trajectory were coded as non-avoidance movement. Note that this dichotomization is based on a rather arbitrary cut-off (ie, the middle line), meaning that this measure is a rough approximation of avoidance versus approach behavior.

Avoidance behavior was operationalized as the (orthogonal) deviation from the avoidance trajectory during the avoidance test of the operant avoidance task, averaged over the entire block. This information was again extracted using the coordinates of each performed movement. The avoidance trajectory serves as 0 value: negative values indicate deviations away from the avoidance trajectory in the direction of the pain-associated trajectory; positive values indicate deviations in the opposite direction, indicating excessive (ie, overprotective) avoidance.

Secondary Outcome Measures

Retrospective pain-expectancy and pain-related fear ratings collected during the directed phase are described in supplementary material.

Avoidance behavior accuracy was operationalized as the *absolute* (orthogonal) deviation from the avoidance trajectory during the avoidance test of the operant avoidance task, averaged over the entire block. Note that this method is identical to the proprioceptive accuracy measure.

Post-experimental questions regarding the experimental procedure were presented at the end of the session. To assess whether participants tried to reproduce the avoidance movement during the avoidance test, they answered the question "*Did you try to perform exactly the same avoidance trajectory from the previous phase?*" with answer options "*Yes*"/"*No*." If yes, the question "*How often did you try to perform exactly the same avoidance trajectory from the previous phase?*" was answered using a Visual Analogue Scale ranging from "*Never*" to "*Always*." See supplementary material for a description of further post-experimental questions.

Psychological trait questionnaires were administered after the experimental procedure to assess fear of pain (the Fear of Pain Questionnaire),[27] positive and negative affect (trait version of Positive And Negative Affect Schedule),[38] intolerance of uncertainty (Intolerance of Uncertainty Scale, 12 item version),[1] distress tolerance (Distress Tolerance Scale),[30] and sensation seeking (Brief Sensation Seeking Scale).[13]

Data Preparation and Analysis

First, data from the DMR task were visually inspected for artifacts. Two participants were excluded for not adhering to task instructions, as they only moved along the edge of the movement plane. Additionally, 5 test trials were excluded (over 4 participants) for reaching the end of the movement plane or initially moving in the wrong direction. Proprioceptive accuracy was calculated using the remaining test trials for these 4 participants. To calculate the avoidance behavior measure, we excluded trials from the first non-avoidance movement onward per participant–using the average orthogonal deviation from the middle line as described for the avoidance proportion measure–because our main interest was in avoidance behavior, and not in exploratory behavior. This decision was preregistered and was based on pilot data where participants reported exploration of the novel movements to find out movement-outcome contingencies, even though they were instructed to avoid. This led to the exclusion of an additional 5 participants who did not avoid on the first trial of the avoidance test, resulting in a final sample size of 41 participants to test our main hypothesis.

Before testing our main hypothesis, we performed a number of manipulation checks. *First,* to test for acquisition of pain-expectancy and pain-related fear, repeated measures analyses of variance (ANOVAs) with within-subjects factors Trajectory (T_{Pain}, T_{Avoid}) and Time (Start, Middle, End) were conducted on ratings during avoidance training. A pairwise comparison between both trajectories at the end of training was used to confirm successful acquisition. *Second*, to check whether participants learned to avoid the pain stimulus, we tested

whether they performed the avoidance trajectory significantly more than the pain-associated trajectory during the second training block using a 1-sample t-test on avoidance proportion (with test value .50, which indicates random movement). *Third*, the same test was run on the avoidance test to check whether participants generalized their avoidance behavior, meaning that we checked whether they performed movements similar to the avoidance trajectory more frequently than movements similar to the pain-associated trajectory. *Finally*, to test our main hypothesis stating that poorer proprioceptive accuracy is associated with excessive avoidance behavior, we calculated Spearman rank correlation coefficient ρ, as proprioceptive accuracy was not normally distributed (Shapiro-Wilk test $P < .05$). A one-sample t-test was added to check whether movements indeed significantly deviated from the avoidance trajectory (with test value 0, which corresponds with the avoidance trajectory), away from the pain-associated trajectory. Furthermore, we explored how proprioceptive accuracy evolved from the DMR task to the avoidance test (ie, avoidance behavior accuracy minus proprioceptive accuracy) in a subsample of participants who reported attempting to reproduce the exact avoidance trajectory during the avoidance test. We used a paired samples t-test to test this, and additionally tested whether this change was associated with any psychological traits using Spearman rank correlations (as change in accuracy was not normally distributed; Shapiro-Wilk test $P < .05$).

Additionally, in supplementary material, we provided a summary of psychological trait questionnaire scores, physical stimulus intensity and subjective stimulus ratings (during calibration and after the experiment), and compared these between the subsample of participants that reported only reproducing the avoidance trajectory during the avoidance test, and the rest of the sample. Furthermore, we analyzed the tendency to move on the outside of the target circle/avoidance trajectory (ie, overshooting) in both the DMR and avoidance tasks and report preregistered exploratory analyses.

For all analyses, the family-wise alpha level was set at .05. Greenhouse-Geisser corrections were applied to control for violations of sphericity in repeated measures ANOVAs, and corrected degrees of freedom are reported together with ε. To control for multiple testing, Holm-Bonferroni corrections were applied. The indication of effect size η_p^2 is reported for significant ANOVA effects, and Cohen's *d* for t-tests. All statistical analyses were performed using jamovi 1.6.23.[33] HapticMaster data was processed using custom-made MATLAB scripts (The MathWorks Inc., Natick, MA).

Results

Confirmatory Analyses

Manipulation Checks

Acquisition of pain-expectancy and pain-related fear. Analysis of pain-expectancy ratings during avoidance training showed a main effect of Trajectory, $F(1, 40) = 45.28$, $P < .001$, $\eta_p = .53$, but not Time, $F(1.67, 66.81) = .27$, $P = .726$, $\varepsilon = .84$. As expected, there was a significant 2-way interaction, $F(2, 80) = 20.02$, $P < .001$, $\eta_p = .33$, indicating that pain-expectancy ratings evolved differently per trajectory during the training phase (Fig 3, panel A). At the end of training, participants expected the pain stimulus to occur more before performing the pain-associated trajectory compared to the avoidance trajectory, $t(40) = 6.80$, $P < .001$, $d = 1.94$.

Furthermore, analysis of pain-related fear ratings during avoidance training showed main effects of Trajectory, $F(1, 40) = 19.61$, $P < .001$, $\eta_p = .33$, and Time, $F(1.38, 55.00) = 4.22$, $P = .033$, $\eta_p = .10$, $\varepsilon = .69$, as well as a significant 2-way interaction, $F(1.57, 62.71) = 14.72$, $P < .001$, $\eta_p = .27$, $\varepsilon = .78$. A pairwise comparison at the end of avoidance training confirmed that participants were more afraid to perform the pain-associated trajectory than the avoidance trajectory, confirming successful differential fear learning (Fig 3, panel B), $t(40) = 4.70$, $P < .001$, $d = 1.14$.

Avoidance proportion during avoidance training and test. As expected, participants performed the avoidance trajectory significantly more ($M = .77$, $SD = .21$) than the pain-associated trajectory during the second block of the

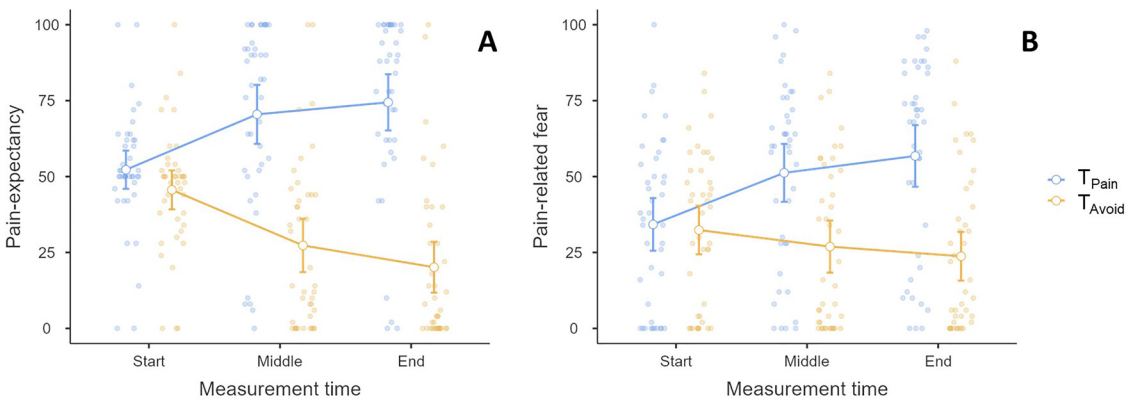

Figure 3. Observed ratings, estimated marginal means, and 95% confidence intervals of pain-expectancy (panel A) and pain-related fear (panel B) ratings for the pain-associated (T_{Pain}) and avoidance trajectories (T_{Avoid}) during the 3 measurement times (Start, Middle, and End) of the avoidance training phase.

training phase, $t(40) = 8.07$, $P < .001$, $d = 1.26$, meaning that participants learned to avoid the pain stimulus. During the avoidance test, participants generally performed movements similar to the avoidance trajectory ($M = .81$, $SD = .23$), $t(40) = 8.69$, $P < .001$, $d = 1.36$, indicating that participants generalized what they learned during training to this phase.

Testing our Main Hypothesis: Is Poorer Proprioceptive Accuracy Associated With Excessive Avoidance Behavior?

The correlation between proprioceptive accuracy and avoidance behavior during the avoidance test was significant, $\rho(41) = .35$, $P = .024$. Furthermore, participants significantly deviated from the avoidance trajectory, away from the pain-associated trajectory (ie, outward; $M = 2.44$, $SD = 4.35$), $t(40) = 3.58$, $P < .001$, $d = 0.56$, indicating a general tendency to be overprotective. These results support our hypothesis that poorer proprioceptive accuracy is associated with excessive avoidance (Fig 4).

Exploratory Analyses

Change in Proprioceptive Accuracy After Avoidance Conditioning

Thirteen of 41 participants (31.71 %) reported attempting to *exactly reproduce the avoidance trajectory* during the entire avoidance test. In this subsample, avoidance behavior accuracy during the avoidance test was significantly reduced compared to proprioceptive accuracy during the DMR task, $t(12) = 2.29$, $P = .041$, $d = .63$. Reductions in accuracy were significantly correlated with avoidance behavior, $\rho(13) = .86$, $P < .001$, indicating they were generally directed away from the pain-associated trajectory. Moreover, reduced proprioceptive accuracy was significantly correlated with trait fear of pain scores, $\rho(13) = .75$, $P = .018$: higher reductions in accuracy were associated with higher trait fear of pain. Correlations between accuracy reductions and other traits did not reach significance (negative affect, $\rho(13) = .60$, $P = .144$; positive affect, $\rho(13) = -.29$, $p = 1.00$; intolerance of uncertainty, $\rho(13) = .24$, $P = .861$; distress tolerance, $\rho(13) = -.18$, $p = .547$; sensation seeking, $\rho(13) = -.27$, $P = 1.00$).

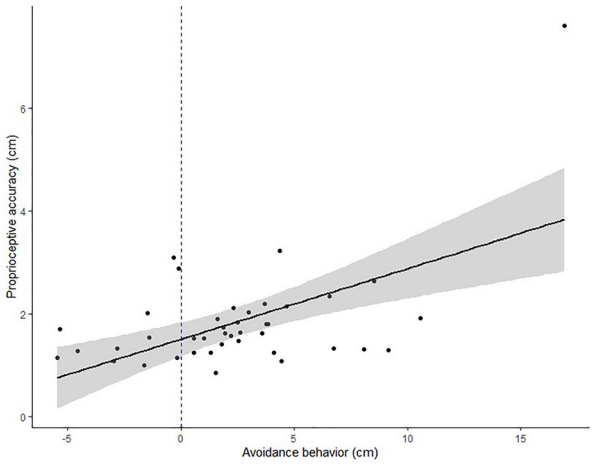

Figure 4. Scatterplot of the association between avoidance behavior and proprioceptive accuracy during the avoidance test. The black line represents a regression line and the gray area a 95% confidence interval. For the avoidance behavior measure, the avoidance trajectory serves as 0 value (represented by the dotted line): negative values indicate deviations away from the avoidance trajectory in the direction of the pain-associated trajectory; positive values indicate deviations in the opposite direction, indicating excessive (ie, overprotective) avoidance. For the proprioceptive accuracy measure, larger values reflect poorer accuracy. (Color version of figure is available online.)

Discussion

The current study investigated the intriguing question whether poorer proprioceptive accuracy is associated with overprotective pain-related avoidance behavior using robotic arm-reaching tasks. First, our manipulation checks showed successful acquisition of self-reported pain-expectancy and pain-related fear, as well as avoidance behavior, confirming that participants learned the movement-outcome contingencies. Furthermore, the learned avoidance behavior successfully generalized toward the avoidance test. Testing of our main hypothesis supported that poor proprioceptive accuracy was associated with excessive avoidance in terms of increased deviation from an avoidance trajectory, away from a pain-associated trajectory. Moreover, exploratory analyses—using a subsample of participants who reported the strategy to exactly reproduce the avoidance trajectory during the avoidance test—showed reduced accuracy during the avoidance test compared to the proprioceptive accuracy test before conditioning. Interestingly, reduced proprioceptive accuracy was associated with overprotective avoidance behavior and higher trait fear of pain.

The finding that poorer proprioceptive accuracy was indeed associated with excessive pain-related avoidance behavior is an innovative and important contribution to the field of chronic pain disability, because poor proprioceptive accuracy has been observed in a wide range of chronic pain conditions.[15,16,31,34] Although we did not establish causality, the found association suggests that such poor accuracy may contribute to disability, as excessive avoidance is considered key in the development and maintenance of chronic pain disability.[37] Because avoidance is a key behavioral correlate of fear,[17] this finding also extends previous work in the field of anxiety disorders, which showed—using visual stimuli—that poor perceptual accuracy is associated with more fear generalization.[32,39,40] However, such studies mainly focused on the relationship between perceptual accuracy and fear responding toward stimuli resembling a threat-associated stimulus, whereas the current study looked at safe avoidance movements.

Our exploratory finding that avoidance learning is associated with a reduction in proprioceptive accuracy extends previous work showing that aversive classical

conditioning reduces perceptual accuracy in a number of modalities (eg, visual, auditory stimuli).[18,29,41] For example, Schechtman, Laufer, and Paz[28] showed increased misperception of novel tones as a conditioned tone after aversive conditioning. Previous work however solely focused on classical conditioning, in which participants passively experience associations between stimuli, and not on operant conditioning, where participants actively adapt their behavior based on learned associations, as in the current study. Furthermore, these studies mainly focused on perceptual changes in stimuli similar to an aversively conditioned stimulus, and to a lesser extent in stimuli similar to a safe stimulus, such as the avoidance trajectory in the current study. However, a study by Shalev, Paz, and Avidan[29] showed no change (or even improvement) in perceptual discrimination thresholds when testing stimuli similar to a safe stimulus. The current study however provides evidence for a reduction in proprioceptive accuracy when trying to reproduce a learned safe movement. Importantly, reductions were associated with avoidance behavior, indicating that it may contribute to avoidance becoming excessive, thus contributing to disability. Moreover, higher reductions were associated with higher trait fear of pain scores. From a predictive processing perspective, this may be due to a "better safe than sorry" processing strategy underlying such traits. This perspective views the brain as a prediction machine that continuously strives to reduce prediction errors.[3] Specifically, the brain attempts to generate a model of the internal and external world using prior knowledge and sensory evidence as input. However, these inputs are weighted (precision weighting); therefore, reduced proprioceptive accuracy may be a result of increased weighting of the affective-motivational aspects of input at the expense of detailed sensory-discriminative input, leading to a stagnated error-reduction process.[35]

Some limitations of the current findings and implications for future studies deserve attention. *First*, the DMR and the operant avoidance tasks both require performance of circular movement trajectories. Future studies may employ unique movements in the operant avoidance task to establish that the effect generalizes to other movements. *Second*, our avoidance behavior measure captures multiple processes, such as variation in generalization of avoidance, proprioceptive accuracy, and exploratory behavior (ie, figuring out movement-outcome contingencies). Proprioceptive accuracy inherently plays a role in such a task, however, future versions could limit exploratory behavior by improving instructions, for example by instructing participants to select a trajectory that is most likely to avoid the aversive outcome, and stick to this trajectory. To limit the role of exploratory behavior in the current study (which was present according to post-experimental questioning), we excluded movements from the avoidance test, starting from the first movement that objectively resembled the pain-associated trajectory more than the avoidance trajectory. However, this approach may have unintentionally omitted movements that actually had an avoidance function, because our cut-off (ie, the middle line) was rather arbitrary, and we did not assess underlying motivations for each movement. The same holds for movements that were included as avoidance movements. *Third*, our measure of proprioceptive accuracy also depends on factors, such as recall and motor control, as is often the case when assessing active proprioceptive function.[5,11] Future studies may benefit from assessing the influence of these specific factors in the association between proprioceptive accuracy and avoidance behavior as found in the current study. *Fourth*, some caution is warranted in interpreting the general tendency to move on the outside of the avoidance trajectory during the avoidance test as excessive avoidance behavior, as this tendency is also present in the DMR task. In other words, there is a general tendency to move on the outside of the target circle during reproduction (overshooting; see supplementary material). Future studies using the current paradigm need to control for this effect. However, movements deviated significantly further in the avoidance test compared to overshooting during the DMR task, indeed indicating the presence of overprotective behavior. *Fifth*, regarding our exploratory analyses, the subsample of participants that attempted to replicate the avoidance trajectory was rather small and "self-selected," as they decided on this movement strategy. It may be that these participants were generally more anxious, thus showing the association between reduced accuracy and trait fear of pain—although exploratory analyses showed no statistical difference with the rest of the sample in trait fear of pain (see supplementary material). Whether the findings regarding change in accuracy still hold when explicitly instructing the full sample to replicate the avoidance trajectory deserves further investigation. *Finally*, the reduction in accuracy could also be due to other factors, such as the addition of vision in the operant avoidance task, as the DMR task was performed blindfolded, thus limiting causal inferences. However, previous work from our lab indicates that the addition of visual cues does not significantly reduce accuracy.[36]

Given the key role of excessive avoidance behavior in chronic pain conditions,[4,19,37] gaining insight into factors that contribute to such behavior is imperative for treatment. The current study is the very first to show that there is an association between proprioceptive accuracy and excessive pain-related avoidance of movements. It should be noted that the sample on which this conclusion is based consisted mostly of bachelor students—thus limiting generalizability—and observed movement deviations were in the order of centimeters. Therefore, these results need validation in clinical populations. Given that excessive spreading (ie, overgeneralization) of pain-related fear and pain-expectancy has been observed in chronic pain samples,[22-24] we expect to observe excessive avoidance in such samples compared to pain-free participants. Furthermore, we expect poorer proprioceptive accuracy, and a significant association between accuracy and avoidance. If this association is indeed present in chronic pain samples, the effect of training proprioceptive accuracy on avoidance behavior deserves investigation to see whether clinically

relevant effects can be obtained. There is preliminary evidence for beneficial effects of proprioceptive accuracy training in chronic neck pain,[14] though underlying mechanisms deserve further attention to inform and optimize treatment. Studies in the field of anxiety disorders have already indicated that training (visual) perceptual accuracy indeed leads to attenuated generalization of fear[8,12] and avoidance,[7,20] thus indicating potential for the field of chronic pain as well.

In conclusion, the current study is the very first to show that poorer proprioceptive accuracy is associated with excessive pain-related avoidance of movements. Furthermore, explorative analyses suggest that avoidance learning leads to reduced proprioceptive accuracy, and that reductions in accuracy are associated with excessive avoidance and trait fear of pain. These findings have important implications for future research as well as clinical practice, as they highlight the potential of targeting proprioceptive accuracy to attenuate excessive avoidance of movements.

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Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jpain.2022.03.233.

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