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A between-subjects investigation of whether distraction is the main mechanism behind music-induced analgesia

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Music- and distraction-induced pain reduction have been investigated extensively, yet the main mechanism underlying music-induced analgesia remains unknown. In this study, to assess whether music-induced analgesia primarily operates through cognitive modulation, we used the cold pressor task and objectively compared the pain tolerances of participants in a four-group between-subjects design: a music group that listened to a music piece in the absence of any tasks, a music-and-attention-to-music group that listened to the same piece while also rating the arousal levels in the music, a music-and-attention-to-pain group that rated their pain levels while listening to the same piece, and a silence group as control. The group passively exposed to music playback did not show significantly higher pain tolerance compared to the silence group. However, pain tolerances in the music group negatively correlated with participants' self-reported arousal ratings of the music at the end of the experiment. The groups that engaged in an active task – whether evaluating the arousal levels in the music or reporting their experienced pain levels – demonstrated similarly higher pain tolerances compared to the silence group. These findings suggest that engaging in a task, regardless of whether it involves exteroceptive or interoceptive attention, can enhance pain tolerance.

Keywords Analgesia, Music, Distraction, Pain Tolerance, Cold Pressor Task

Analgesia - the alleviation of pain - can be achieved through various means, from pharmacological analgesic agents to top-down psychological modulation[1–4]. Music has also attracted considerable interest as a potential therapeutic intervention for pain management[5–7]. Although recent meta-analyses of randomized controlled trials[8] and studies using experimentally induced pain in healthy participants[9] concluded that music interventions effectively reduce pain, the exact psychological mechanisms of music-induced analgesia remain unknown. The distractive effect of music that directs attention away from one's suffering has been proposed as one of the major mechanisms inducing pain relief, together with other potential mechanisms, such as emotional regulation and cognitive agency[5–7]. Indeed, setting listening to music aside, it has long been known that cognitive distraction alone effectively decreases experimentally induced pain in healthy participants[10–12]. The present study aimed to assess whether the major mechanism behind music-induced analgesia is cognitive distraction.

Few studies compared the analgesic effects of music and distraction. Mitchell et al.[13] measured pain tolerances using the well-established and widely used cold pressor task[14], in which the participants were asked to place their hands in a bucket filled with cold water as long as they could withstand the pain. The latency to withdraw hands from the cold water was taken as an objective measure of pain tolerance. Using a repeated-measures design, Mitchell et al. compared pain tolerances, as well as self-reported pain intensities, across conditions in which participants listened to their favorite music piece, listened to a humorous snippet of a comedy show, or engaged in the Paced Auditory Serial Addition Task (PASAT) for cognitive distraction. Pain tolerances were significantly higher in the music compared to the distraction condition but not different from the humor condition, although the perceived pain ratings were comparable in all conditions. Ruscheweyh et al.[15] also used a within-subjects design to compare the analgesic effects of listening to preferred music, imagining a pleasant experience, and counting the times a brush struck their fingers as the distraction condition. Electrical pain was applied to participants' lower limbs and the resulting nociceptive flexor reflexes and perceived pain ratings were collected as outcome measurements. Results showed that although subjective pain ratings were reduced in all three conditions, the reflexes were only reduced in the cognitive distraction condition. Silvestrini et al.[16]

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compared the effects of pleasant and unpleasant music and cognitive distraction induced through an auditory attention task on pain tolerances in the cold pressor task, nociceptive flexion reflex, and subjective pain ratings using a repeated-measures design. Pleasant, but not unpleasant, music and cognitive distraction were found to be similarly effective in increasing pain tolerances and decreasing subjective pain ratings, but not nociceptive reflexes. Finally, Garza-Villareal et al.[17] used thermal pain to compare the effects of listening to unfamiliar music, non-musical sounds, and pink noise, and engaging in PASAT for cognitive distraction on perceived pain ratings in a within-subjects design. Distraction was found to be the most effective, followed by listening to music and non-musical sounds, which were not different from each other and were both more effective than pink noise in reducing subjective pain intensity reports. These studies not only revealed largely conflicting results, but also all used research designs that only allowed to compare the effect sizes of the potential analgesic effects of distraction and music, which is very different than the question we are addressing in the present study: does listening to music induce its potential analgesic effect predominantly through cognitive distraction? Addressing this question requires the elimination of the potential distractive element of music as a critical condition to reveal the mechanism underlying music-induced analgesia. Therefore, in the present study, we aimed to reduce the potential distractive effect of music by directing the focus directly onto participants' own pain experiences in one of the experimental conditions, which allowed us to address this critical question.

In an influential study, Mitchell and MacDonald[18] showed that pain tolerances as measured in the cold pressor task were higher when participants listened to their own pre-selected music that they brought to the experiment as compared to a relaxing music piece that was chosen by the experimenters, which did not induce a stronger effect than the white noise control stimulus. Meta-analyses on clinical populations confirmed that self-selected music leads to superior analgesic effects[19,20]. These results could be interpreted as indicating the analgesic effect of the enjoyment that participants experience by listening to familiar music and/or the analgesic effect induced by the experience of control over the selection of music. To dissect these two potential effects from each other, Howlin and Rooney[21] gave participants pseudo-options to make them experience the perceived control of choice, when in fact the musical pieces that would eventually be played during the cold pressor task were predetermined by the experimenters. When enjoyment was controlled for, the perceived choice was found to be an effective predictor of pain tolerances, which was interpreted as indicating that increased cognitive agency was an important element of music-induced analgesia. Nevertheless, these findings could also be interpreted as showing the effect of demand characteristics on the cold pressor task. That is, overtly asking participants to choose musical pieces to be played during a pain task might lead them to presume that self-chosen music would have pain-relieving effects. In turn, they might perform in the cold pressor task, either consciously or unconsciously, in a way that aligns with these presumptions. Indeed, beliefs and expectations alone are very well known to induce analgesic effects, such as in the case of placebo analgesia[22,23]. The potential effect of demand characteristics is in fact a much more serious problem that might create confounding effects in studies using within-subject designs, as in all of the studies that compared the effects of music and distraction reported in detail above. Simply subjecting the participants to all experimental conditions one by one might inevitably allow participants to generate presumptions as to which condition might generate a stronger analgesic effect than another condition, and thus direct the participants to act accordingly during pain assessments. Lunde et al.[24] conducted an experimental assessment of the contribution of the placebo effect to music-induced analgesia in a within-subjects design and showed that the pain-relieving effect of music is partially mediated by subject expectancy effects. In the present study, we employed a fully between-subjects design to ensure that participants were only subjected to a single condition, and thus were unaware of the alternative conditions. This way, we hoped to minimize the demand characteristics that could potentially enable participants to understand the critical comparisons in the study, which might confound the analgesic effects of music exposure.

In the present study, we divided our sample into four conditions: a music group that listened to an experimenter-selected classical music piece in the absence of any explicit tasks, a music-and-attention-to-music (MAM) group that listened to the same piece while also rating the arousal levels in the music piece, a music-and-attention-to-pain (MAP) group that rated their pain levels while listening to the same piece, and a silence group as control (Fig. 1a). The MAP group served as the critical experimental condition, in which the participants heard the music piece; however, any potential distractive effect of music was blocked by explicitly asking participants to focus on their pain experiences. The MAM group subserved a critical control condition, in which, similar to the MAP condition, there was an explicit task that participants were required to engage in, but the focus was directed to the music piece, instead of the pain experience. Thus, the MAP group directed their attention towards an interoceptive cue, to their pain; while the MAM group directed their attention towards an exteroceptive cue, the music. We used the cold pressor task to objectively quantify pain tolerances by measuring how long participants could keep their hands in cold water. After the cold pressor task, participants were asked to complete the Positive and Negative Affect Schedule (PANAS) to evaluate their mood, and they rated the musical piece they heard in terms of valence, arousal, and liking. We first hypothesized that the pain tolerances would be higher in the music compared to the silence condition. We further hypothesized that, if the analgesic effect of listening to music is induced predominantly through cognitive distraction, then eliminating this distraction and purposefully directing participants' attention to their own pain experiences in the MAP group would lead to pain tolerance levels lower than those in the music condition and similar to those in the silence condition. Under this hypothesis, pain tolerances in the MAM group would be similar to or even higher than those observed in the music group, since participants' attention would be explicitly directed to the music piece, potentially strengthening the distractive effect of listening to music. If, on the other hand, music-induced analgesia is not strongly mediated by cognitive distraction, then directing participants' attention to their pain experiences would have little effect on pain tolerances, since these participants would still be perceiving the music piece. Thus, under this alternative, the pain tolerance levels in the MAP condition would be higher than those in the silence condition and similar to those in the music condition.

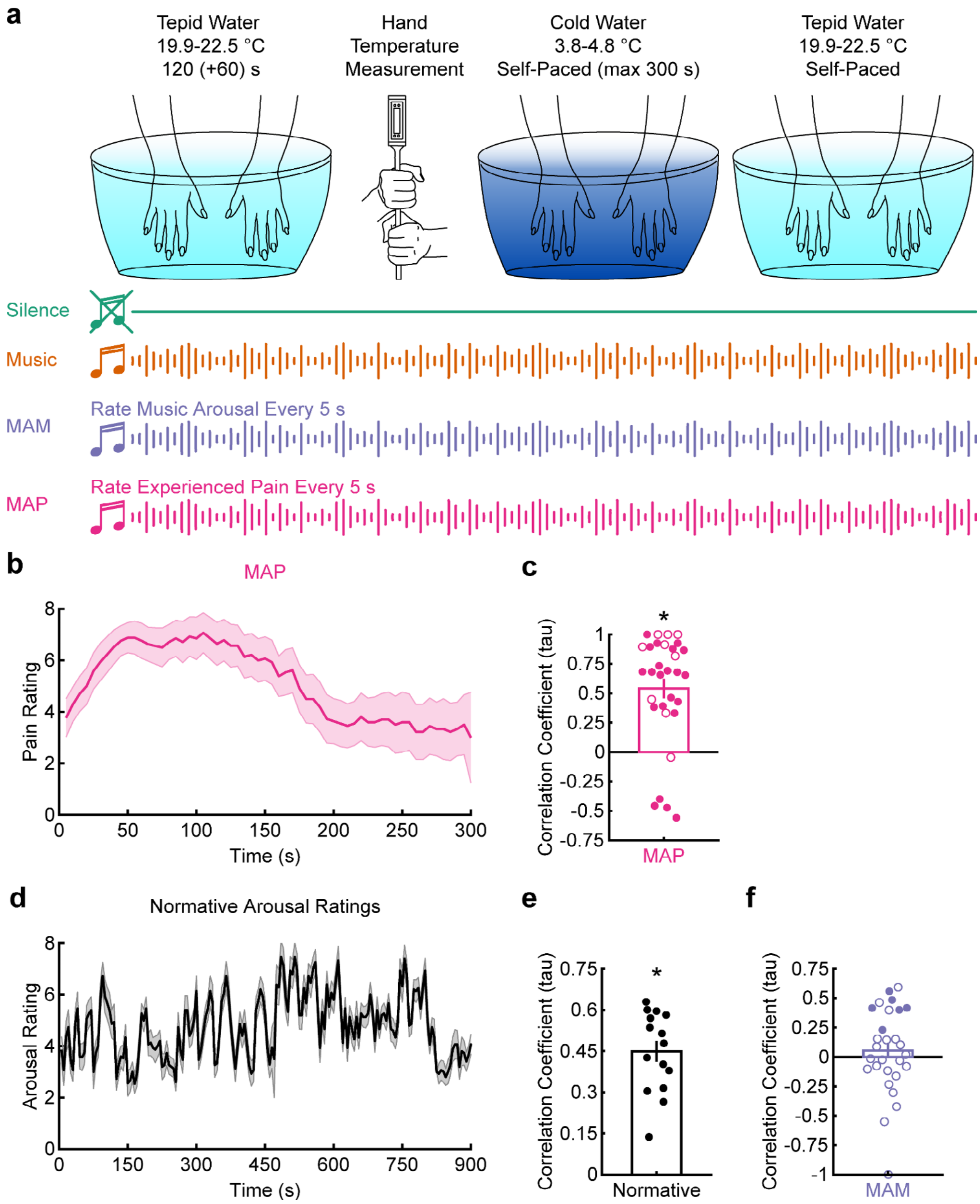

Fig. 1. Experimental procedure, pain ratings, and music arousal ratings. **(a)** In a between-subjects design, participants were randomly allocated to one of four conditions: a music group that listened to an experimenter-selected classical music piece in the absence of any explicit tasks, a music-and-attention-to-music (MAM) group that listened to the same piece while also rating the arousal levels in the music piece, a music-and-attention-to-pain (MAP) group that rated their pain levels while listening to the same piece, and a silence group as control. Music playback was started before the participants entered the experimental room. Before the cold pressor task, participants first placed their hands in the tepid water for 120 s (and additionally for 60 more seconds if needed) to bring their hand temperatures to comparable levels, which was verified via thermometer measurements. Then, participants placed their hands into the cold water for as long as they could tolerate it or for a maximum duration of 300 s. The latency to withdraw hands was taken as a measure of pain tolerance. Participants used the tepid water tank again as long as they pleased to bring their hand temperature to comfortable levels. **(b)** Mean pain ratings in the MAP group during the cold pressor task. **(c)** Correlation coefficients between each participant's pain ratings and the average of all the other participants' pain ratings in the MAP group during the cold pressor task. **(d)** Mean normative music arousal ratings in the validation study. **(e)** Correlation coefficients between each participant's music arousal ratings and the average of all the other participants' music arousal ratings in the validation study. **(f)** Correlation coefficients between the music arousal ratings of each participant in the MAM group during the cold pressor task and the average normative music arousal ratings in the validation study. Shadings and error bars indicate standard errors of the means. Filled and empty circles indicate statistically significant and nonsignificant correlation coefficients, respectively. Asterisks indicate statistically significant one-sample Wilcoxon signed-rank tests.

Results

Manipulation checks and control variables

We started our analyses by verifying that our instruction manipulations were effective. Firstly, we assessed whether the participants in the music-and-attention-to-pain (MAP) group indeed directed their attention to their pain and reported it reliably (Fig. 1b). In the absence of any objective means of measuring participants' pain levels, we analyzed the internal consistency of the pain ratings during the cold pressor task by calculating, for each participant separately, the correlation coefficient between the time-varying pain ratings of that particular participant and the average pain ratings of all the remaining participants in the same group. The correlation coefficients were significantly positive at the group level ($W = 457$, $p = 4 \times 10^{-5}$, Fig. 1c). The numbers of participants who had positive correlations (18/31, 58%, $p = 2 \times 10^{-21}$) and negative correlations (4/31, 13%, $p = 0.007$) were both higher than what would be expected under the null hypothesis, as indicated by binomial tests. Consistent temporal patterns of pain ratings among the participants suggest that the participants in the MAP group reliably attended to their pain levels during the cold pressor task.

We next tested whether the participants in the music-and-attention-to-music (MAM) group successfully directed their attention to the arousal levels of the music. To obtain normative arousal ratings of the music piece we used in the experiment, we had a separate sample of 15 participants rate the arousal of the music every 5 s under normal listening conditions in a validation study (Fig. 1d). We measured the internal consistency of the validation ratings by calculating participant-specific correlation coefficients employing the method explained above for pain rating manipulation checks. There was a significant positive correlation at the group level, providing strong support for the internal consistency of the normative arousal ratings ($W = 120$, $p = 6 \times 10^{-5}$; Positive: 15/15, 100%, $p = 9 \times 10^{-25}$; Fig. 1e). We then calculated the correlation coefficient between the time-varying arousal ratings of each participant in the MAM group and the average time-varying normative arousal ratings to assess whether the participants indeed rated the arousal level of the music as instructed. The correlation coefficients were not significantly different from zero at the group level ($W = 246$, $p = 0.339$, Fig. 1f). Nevertheless, the number of participants who showed positive correlations was significantly greater than the chance level (6/28, 21%, $p = 6 \times 10^{-5}$). These results suggest that the arousal ratings of only a few participants in the MAM group were related to the normative arousal ratings of the same musical piece.

We also verified that the four experimental conditions did not significantly differ from each other in subject characteristics such as gender distribution, age, PANAS positive, and PANAS negative scores, as well as procedural parameters such as the temperatures of the weather during the experimental session, the temperatures of the tepid and cold waters, and the temperatures of their hands at the beginning of the cold pressor task (Table 1). Furthermore, the three groups that were presented with the music during the experiment reported comparable overall music liking, valence, and arousal ratings after the cold pressor task (Table 1).

Pain tolerances

As illustrated in Fig. 2a, pain tolerances were bimodally distributed, consisting of a lower mode resembling a positively skewed normal-like distribution and a higher mode with the majority of the pain tolerance values accumulated at the maximum possible level (300 s). Due to the serious violations of normality, experimental groups were compared using nonparametric statistical tests. Our experimental manipulations had a significant effect on pain tolerances ($H = 12.360$, $p = 0.006$, Fig. 2b), which was further examined via six separate pairwise comparisons with a Bonferroni-corrected alpha level of $0.05/6 = 0.0083$. Pain tolerances in the music group were numerically greater than those in the silence group, however, this difference was not statistically significant

	Condition				Kruskal-Wallis Test	
Variable	**Silence**	**Music**	**MAM**	**MAP**	***H***	***p***
Gender	22/9	25/6	23/7	24/7	-	0.375
Age	21.52 ± 1.77	21.26 ± 1.29	21.37 ± 1.50	20.84 ± 1.32	3.355	0.340
PANAS Positive	3.11 ± 0.55	3.06 ± 0.67	2.97 ± 0.74	2.87 ± 0.59	4.008	0.261
PANAS Negative	1.65 ± 0.58	1.47 ± 0.53	1.75 ± 0.70	1.77 ± 0.69	4.769	0.190
Weather Temperature	10.40 ± 3.28	11.85 ± 3.32	12.02 ± 2.74	11.22 ± 3.39	4.418	0.220
Tepid Water Temperature	20.86 ± 0.44	20.73 ± 0.52	20.87 ± 0.39	20.82 ± 0.39	3.349	0.341
Cold Water Temperature	4.25 ± 0.30	4.31 ± 0.27	4.23 ± 0.30	4.30 ± 0.28	1.779	0.619
Hand Temperature	24.82 ± 2.68	24.27 ± 3.15	24.05 ± 2.35	24.11 ± 2.78	2.336	0.506
Music Liking	-	7.03 ± 2.15	6.24 ± 2.08	6.77 ± 1.98	2.389	0.303
Music Valence	-	6.32 ± 2.39	5.21 ± 2.26	5.61 ± 2.12	3.925	0.141
Music Arousal	-	4.90 ± 2.74	5.62 ± 2.35	5.45 ± 2.34	1.180	0.554

Table 1. Descriptive and inferential statistics of the control variables across the experimental conditions. Descriptive statistics of gender are reported as female/male and all the others are reported as mean ± sd. Age values are in years and temperature values are in °C. MAM and MAP stand for the music-and-attention-to-music group and the music-and-attention-to-pain group, respectively. *H* is the Kruskal-Wallis test statistic. *P* for gender stands for the lowest *p* obtained by six pairwise comparisons of gender proportions. The alpha value for statistical significance was Bonferroni-corrected at $0.05/11 = 0.0045$.

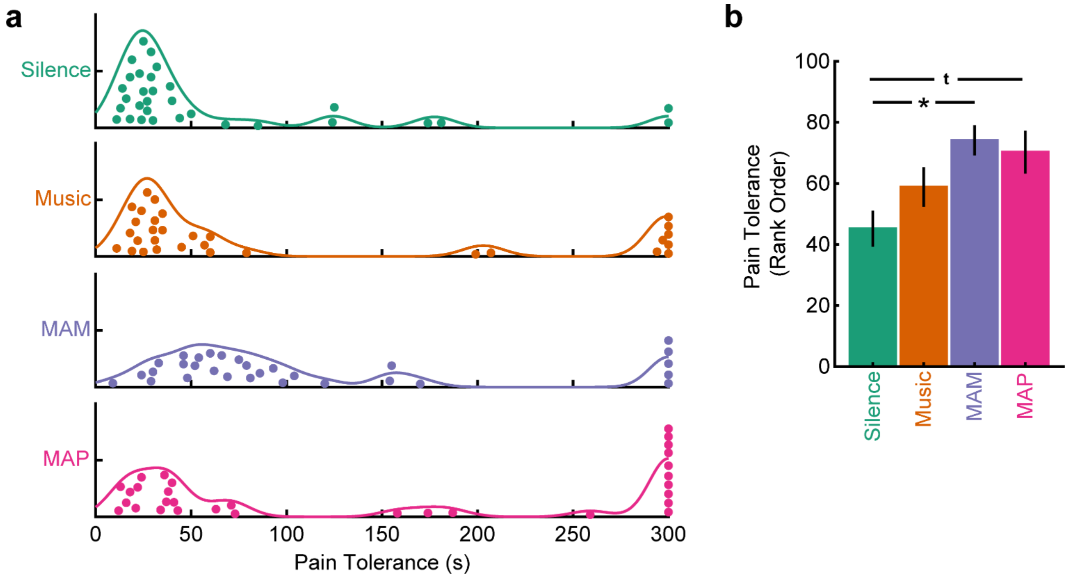

Fig. 2. Pain tolerances across experimental conditions. **(a)** Pain tolerances across the silence, music, music-and-attention-to-music (MAM), and music-and-attention-to-pain (MAP) groups exhibited largely bimodal distributions, consisting of a lower mode resembling a positively skewed normal-like distribution and a higher mode with the majority of the pain tolerance values accumulated at the maximum possible level (300 s). **(b)** Mean pain tolerances of the four experimental groups. Error bars represent the standard errors of the means. Note that the pairwise comparisons were carried out using nonparametric Mann-Whitney U tests. Due to the highly skewed nature of pain tolerances, the rank orders, instead of the raw values, of pain tolerances are used for visualization purposes in the figure. The asterisk indicates the pairwise comparison which was statistically significant at the Bonferroni-corrected alpha level and the t indicates the pairwise comparison which was statistically significant at the uncorrected alpha level.

($W = 363.5$, $p = 0.101$). Pain tolerances in the MAM group, on the other hand, were significantly greater than those in the silence group ($W = 236.5$, $p = 0.001$, rank-biserial correlation = 0.491). Similarly, pain tolerances in the MAP group had a very strong trend towards being greater than those in the silence group, although the statistical significance fell just short of the Bonferroni-corrected alpha level ($W = 304.5$, $p = 0.013$, rank-biserial correlation = 0.366). The MAM and MAP groups did not differ from each other ($W = 473.5$, $p = 0.907$), and both had pain tolerances that were numerically, but not statistically, greater than the music group (MAM vs. music: $W = 592$, $p = 0.067$; MAP vs. music: $W = 392$, $p = 0.212$). Taken together, these findings indicate that engagement in a task, whether attending to an external music stimulus or monitoring internal pain experiences, increases pain tolerance compared to basal conditions. In contrast, simply being exposed to a music stimulus without any additional tasks might possibly produce a somewhat intermediate effect.

We also examined whether our control variables correlated with pain tolerances. Notably, the only significant correlation was a negative one between pain tolerances and how arousing the music was rated by the participants at the end of the experiment only in the music group ($tau = -0.536$, $p = 6 \times 10^{-5}$, Fig. 3a; Table 2). We assessed whether participants with higher pain tolerances might have indeed listened to the less arousing (thus more relaxing) parts of the music by calculating the average normative arousal ratings of the parts of the music that each participant in the music group heard while they were in the experimental room. We then calculated the correlation coefficient between these normative arousal ratings and participants' pain tolerances and, surprisingly, found a significant positive correlation between them ($tau = 0.612$, $p = 3 \times 10^{-6}$, Fig. 3b). This finding suggests that the participants with higher pain tolerances in fact listened to the more arousing parts of the music, and thus the differences in the arousing levels of the music piece could not contribute to the negative correlation we found between participants' own arousal ratings and pain tolerances. A partial correlation analysis between pain tolerances and participants' own arousal ratings, controlling for the variation in normative arousal ratings, still yielded a significant negative correlation ($tau = -0.434$, $p = 0.001$), confirming this conclusion. Thus, not the actual arousal levels in the music, but the perceived arousal levels of the participants in the music group seem to be negatively correlated with their pain tolerances.

Discussion

We used a between-subjects design to assess whether listening to music decreases pain tolerances and, if so, whether this effect is mediated by cognitive distraction that diverts attention away from one's pain. We did not find significantly higher pain tolerances in the group passively exposed to music playback compared to the group in silence. Nevertheless, interestingly, the pain tolerances in the music group were negatively correlated with the music arousal ratings that the participants reported at the end of the experiment. The music-and-attention-to-music (MAM) and the music-and-attention-to-pain (MAP) groups exhibited higher pain tolerance levels

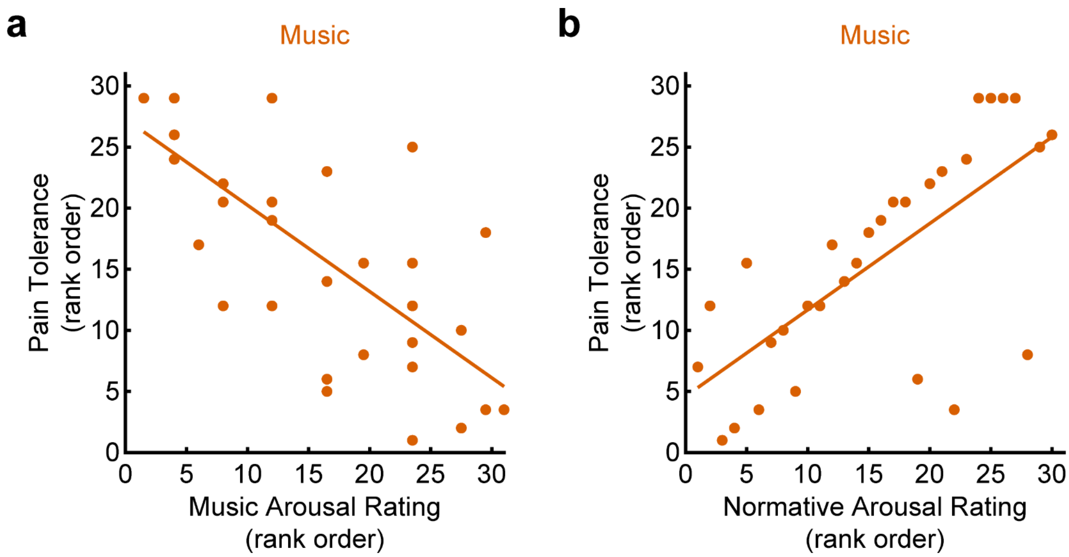

Fig. 3. Music arousal and pain tolerance correlations. **(a)** Scatter plot depicting the correlation between music arousal ratings collected at the end of the cold pressor task and pain tolerances in the music group. **(b)** Scatter plot depicting the correlation between pain tolerances and the normative music arousal ratings during the parts of the music to which the participants in the music group listened. Note that both analyses were carried out using nonparametric Kendall's Tau correlation analyses. Due to the highly skewed nature of pain tolerances, the rank orders, instead of the raw values, of pain tolerances and arousal ratings are used for visualization purposes in these figures. Simple linear regression lines are also overlayed on the figures for visualization purposes.

	Condition							
	Silence		Music		MAM		MAP	
Variable	*Tau*	*p*	*Tau*	*p*	*Tau*	*p*	*Tau*	*p*
Age	−0.123	0.359	−0.288	0.039	−0.120	0.389	−0.313	0.027
PANAS Positive	0.168	0.195	0.157	0.230	0.052	0.693	0.132	0.322
PANAS Negative	0.140	0.288	−0.204	0.127	0.119	0.369	−0.162	0.224
Weather Temperature	−0.181	0.170	−0.102	0.448	0.123	0.366	0.162	0.235
Tepid Water Temperature	0.045	0.732	−0.367	0.005	−0.005	0.971	0.000	1.000
Cold Water Temperature	0.134	0.311	0.018	0.890	−0.244	0.071	−0.158	0.246
Hand Temperature	−0.022	0.865	−0.097	0.452	−0.131	0.316	−0.009	0.945
Music Liking	-	-	−0.014	0.917	0.000	1.000	0.088	0.525
Music Valence	-	-	0.137	0.314	−0.132	0.341	0.148	0.278
Music Arousal	-	-	−0.536	6×10^{-5}	0.169	0.227	−0.027	0.847

Table 2. Results of correlation analyses between pain tolerance levels and the control variables across the experimental conditions. MAM and MAP stand for the music-and-attention-to-music group and the music-and-attention-to-pain group, respectively. *Tau* is the Kendall's tau correlation statistic. The alpha value for statistical significance was Bonferroni-corrected at 0.05/37 = 0.0014.

compared to the silence group, suggesting that participation in a task, whether reporting the arousal levels in an external music piece or reporting experienced pain levels, increases pain tolerance.

Interestingly, the pain tolerances measured in the present study exhibited a strongly bimodal distribution, revealing a lower mode resembling a positively skewed normal-like distribution and a higher mode at the 5-minute time limit of the cold pressor task. This pattern suggests that participants who could withstand the cold water up until a certain time point could then continue to keep their hands in the cold water until the termination of the task. Although it is possible that potential individual differences not measured in the present study could account for such a bimodal distribution of pain tolerances, we believe that this pattern might have instead stemmed from the fact that the cold water temperature was not held constant throughout the cold pressor task. Other studies used circulating cold water systems to keep the water temperature constant throughout the task[13,21,25,26], whereas we verified that the cold water temperature was within the desired range (3.8–4.8 °C) at the beginning of the task and left it untouched afterwards. Considering the fact that the cold water temperature would increase more as some participants kept their hands longer in the cold water, it is possible that some participants reached a point at which the water temperature dropped to a tolerable level and thus they were able to keep their hands in the cold water until the maximum duration of 300 s. Following this rationale, if the initial temperature of the cold water had remained constant, participants who constituted the higher mode of the bimodal distribution we found could potentially remain within the positive tail of the lower mode, resulting in a unimodal distribution of pain tolerances. The temporal pattern of pain ratings depicted in Fig. 1b indicates that pain ratings first increased, but then decreased and remained constant after a certain time point in the cold pressor task. This can also be taken as an indirect support for the argument that participants who could keep their hands in the cold water up until a certain time point then did not feel as much pain in the remaining of the cold pressor task and thus could continue until the termination of the task. Unfortunately, previous studies did not examine and/or report in detail the distributional characteristics of pain tolerances. Whether similar bimodal pain tolerance distributions are also observed under constant cold water temperature conditions needs to be investigated in future studies.

In contrast to our main hypothesis, participants who listened to a music piece in the absence of any explicit tasks did not demonstrate significantly higher pain tolerances compared to those in the silence condition. Several studies used participant-selected music to examine music-induced analgesia[13,18,21,27,28]; however, we used a classical music piece from Mozart as the experimenter-selected stimulus, which has been previously shown to induce analgesia[17]. We opted to use experimenter-selected rather than participant-selected music to maximize the probability that the participants were unaware of the fact that music playback was a critical factor in the study. Our rationale was that if participants were asked to select a music piece before participating in the cold pressor task, they might, either consciously or unconsciously, generate predictions about the purpose of the study and accordingly perform in line with their predictions, running the risk of confounding our attempts to assess music-induced analgesia as cleanly as possible. We not only used a between-subject design, but also started the music playback before the participants entered the experimental room as if it was background music in order to ensure that participants' attention was not directed to the music so that the risk of them understanding that the study was about music-induced analgesia was minimized as much as possible. The great majority of previous studies investigating music-induced analgesia on pain tolerances using the cold pressor task used within-subjects designs[13,18,21,25,26,29–32] or in a few cases, used between-subjects designs, but made it fairly transparent to the participants that the music playback was a critical experimental parameter[33,34]. Other studies have successfully employed between-subjects designs, yielding valuable insight into the effects of agency and expectancy on music-induced analgesia by assessing pain intensity and unpleasantness ratings through self-reports (e.g[28,35]). , instead of measuring pain tolerances via the cold pressor task as utilized in the present study. In the present study, we aimed to assess the analgesic effect of being exposed to music playback on pain tolerances as measured in the cold pressor task as free of demand characteristics as possible. The absence of pain tolerance differences between the music and silence conditions in the present study raises the question of whether simply being exposed to a background musical stimulus, which the participant did not actively select, might fail to induce a strong analgesic effect. However, it is important to be cautious in generalizing this null finding, given that different musical stimuli other than the classical music piece we used in the present study and/or participant-selected music might have induced analgesia in the same experimental design.

Although we did not find a significant pain tolerance difference between the music and silence conditions, there was a negative correlation between pain tolerances and the music arousal ratings that the participants reported at the end of the cold pressor task. This negative association suggested that participants who reported the music to be more relaxing (less arousing) tended to have higher pain tolerances. Prior research indicated that how arousing a music piece is perceived might mediate the effect of music on pain perception[36]. Although at first sight, our findings might seem to also indicate that a small analgesic role of listening to music might be mediated by how relaxing people find a specific music piece to be, we have to be cautious in drawing such interpretations since the arousal reports were collected after the cold pressor task and thus might have been very well affected by participants' performances on the cold pressor task. That is, it is possible that participants who tolerated the cold water pain better might have had a more relaxed state themselves, which might have led them to perceive the music piece as less arousing. We checked and ruled out the possibility that the participants who tolerated the cold water pain for longer durations listened to the parts of the music piece that were indeed less arousing. In fact, the opposite was true: Participants with high pain tolerances listened to the later parts of the music, which were rated to be relatively more arousing than the earlier parts by an independent sample of participants in a validation study. Thus, variations in the arousal aspects within the music stimulus itself cannot explain the relation we found between arousal ratings and pain tolerances. It is important to acknowledge that these findings are correlational in nature, and thus the potential effect of arousal/relaxation properties of music on pain perception needs to be tested in causal research studies employing between-subjects designs and carefully controlling all possible demand characteristics.

The manipulations we implemented to investigate whether distraction is the predominant mechanism underlying music-induced analgesia revealed that significantly higher pain tolerances compared to the silence condition were observed in the MAM group who explicitly rated the arousal levels of the music every five seconds during the cold pressor task. The MAP group, which monitored their experienced pain levels and reported them every five seconds, also had similarly high pain tolerances, which had a strong trend towards being significantly greater than the silence condition. How could these two different manipulations might have generated the same effects on pain tolerances? We believe there are two possible explanations. One possibility is that, although we designed the MAM group to attend to external music to direct their attention away from their own pain, and the MAP group to explicitly focus on their pain experiences, both manipulations may have similarly acted as cognitive distractions. The focus of attention was different in the two groups, however, the act of engaging in a task in which the participants verbally reported a rating every five seconds was exactly the same in the two groups. Thus, it is possible that the engagement in the rating task alone might have worked as a cognitive distraction similarly in both of the groups, yielding similarly positive effects on pain tolerances. Previous studies did not directly assess whether distraction is the dominant mechanism by which music induces pain relief; instead, they examined the role of distraction and music on pain experiences separately and found that cognitive distraction via actively engaging in a task can decrease pain perception[13,15–17]. We purposefully designed the MAM and the MAP groups to follow the same task protocol of rating, differing only in terms of where attention would be directed, to ensure that any potential differences between the groups could not be attributed to the presence or absence of a verbal rating task in one or the other condition. Although we cannot rule out the possibility that reporting verbal ratings might have acted as a cognitive distraction, it is important to emphasize that the participants in the MAP group did attend to their pain experiences between reporting pain ratings. Thus, if, as initially predicted, attending to experienced pain levels would be detrimental to analgesic effects, one might expect to find that the positive effect of cognitive distraction induced by providing verbal reports and the negative effect induced by attending to internal pain experiences would tend to cancel each other, leading to pain tolerances that are not different than the silence condition. It is also important to note that the current study lacked an additional control group in which the participants engaged in a distraction without any music playback. Accordingly, we were unable to assess whether the music playback provides any additional analgesic effect on top of the above-mentioned effects of distraction.

The other possible explanation for the similar results we found in the MAM and the MAP groups is that pain tolerance improvements can be induced not only via cognitive distraction induced by directing attention to external signals, but also via focusing on one's own experienced pain levels. Keogh et al.[37] used the cold pressor task to compare the pain tolerances, as well as the self-reported sensory pain ratings, between groups of participants who were instructed to focus on or try to avoid all sensory experiences during the task. Pain tolerances were comparable between the two groups, but male participants reported lower sensory pain ratings in the focused compared to the avoidance group. McCaul and Haugtvedt[11] compared participants' self-reported distress ratings throughout the cold pressor task between attention, distraction, and control groups. Distraction reduced distress ratings during the early stages of the task, but focusing on one's own pain decreased distress ratings in the later stages of the task, suggesting that the potential analgesic roles played by the two opposing strategies might differ from each other based on the duration of the painful stimulation. In parallel to these findings, detailed observation of the distributions depicted in Fig. 2a suggests that there were relatively more participants who withstood the cold pain until the end of the cold pressor task in the MAP group (10/31) compared to the MAM group (5/30), suggesting that it might indeed be more a long-lasting strategy to attend to one's own pain compared to attending to an external signal. It would be interesting to assess in future studies whether this simple post hoc observation is indicative of a true difference between the analgesic potentials of these two attentional strategies. More broadly, the possibility that both interoceptive attention to pain experiences and exteroceptive attention to external stimuli lead to similar improvements in pain tolerance through different mechanisms can stimulate new research on the neural mechanisms underlying pain analgesia.

Materials and methods
Participants
In total, 132 university students participated in the present study in exchange for bonus course credits. Five participants were excluded since they reported taking a painkiller within the 24 h preceding the experiment. One participant was excluded since the experimental room needed to be evacuated prematurely due to an emergency. One participant in the music-and-attention-to-music (MAM) group was excluded since, at the end of the experiment, they reported that they rated their own arousal levels, not the arousal levels in the music, during the cold pressor task. One participant was excluded since the beginning temperature of the cold water could not be lowered to the desired levels on time before starting the cold pressor task. Finally, one participant was excluded since their age was an extreme outlier within the sample (42 years old, $z = 8.66$). The final sample consisted of 123 participants aged between 18 and 25 years old (mean ± sd = 21 ± 2 years old, female/male = 94/29). None of the participants included in the study reported hearing loss or diagnosis with a neurological or psychiatric condition that is known to impair pain perception in the last three years. Participants were randomly allocated to one of the four conditions (silence, music, music-and-attention-to-music [MAM], and music-and-attention-to-pain [MAP]) and all groups consisted of 31 participants, except for the MAM group, which consisted of 30 participants. The allocation of participants to experimental groups was completely randomized to ensure no systematic differences in basal pain tolerances or any other physiological or psychological factors that might influence pain tolerances. All procedures were approved by the Koç University Committee on Human Research (2023.329.IRB3.149) and each participant read and signed a written informed consent according to the Declaration of Helsinki before participating in the study.

Stimuli
As the musical stimulus, we used Mozart's Divertimento in E-Flat Major, K. 563, II. Adagio and III. Menuetto: Allegretto – Trio pieces. The II. Adagio part was used since it was previously shown to induce a significant analgesic effect compared to pink noise[17] and the III. Menuetto: Allegretto – Trio part had to be used for participants who stayed in the experimental room for longer than intended since it naturally followed the II. Adagio part. To hide the true purpose of the study from the participants as much as possible, we did not start the music playback after the participant entered the experimental room. Instead, the playback was started before the participant entered the room so that the participant could perceive it as background music, which would reduce the risk of demand characteristics that could potentially cause the participants to understand that the study was investigating the effect of music on pain tolerance. The music was played at a mean amplitude of 57 dB through speakers of a laptop that was placed 135 cm from the participant. We obtained normative arousal ratings of the

same musical piece from a separate group of 15 participants who rated their perceived arousal on an 11-point scale every five seconds of the musical piece under normal listening conditions. During this validation study, a 910-second-long segment of the musical piece was presented to the participants to obtain exhaustive normative arousal ratings for the musical piece. Because we started the music playback before the participants entered the experimental room and because different participants started the cold pressor task with somewhat different lags after entering the experimental room (see *Procedure* for details), different participants heard different parts of the musical piece during the task. Hence, collecting the normative ratings from the entirety of the musical piece ensured that normative arousal rating information was available for the parts of the music that all participants heard during the cold pressor task.

Cold pressor task

To assess pain tolerances, we used the cold pressor task, which is a commonly employed reliable technique to objectively quantify pain tolerances[14,38]. Before the beginning of the cold pressor task, the participants were required to place both of their hands into a rectangular bucket (length x width x height = 24 × 15 × 11.5 cm) filled with water at room temperature (mean ± sd = 20.8 ± 0.4 °C, min-max = 19.9–22.5 °C) for two minutes (Fig. 1a). This was done to ensure that the hand temperatures of participants were within equivalent levels before the beginning of the cold pressor task. The hand temperatures of the participants were measured using a thermometer, and if they were not within the 20–30 °C temperature range, the participants were asked to keep their hands for one more minute in the same water bucket. Their hand temperatures were measured again and then they were taken to the cold pressor task. In the cold pressor task, the participants were asked to place both of their hands into a cylindrical bucket (diameter x height = 20 × 24.5 cm) filled with water that was prepared to be within 3.8–4.8 °C (mean ± sd = 4.3 ± 0.3 °C, min-max = 3.8–4.8 °C) right before the participants placed their hands into it. The temperature of the cold water was not fixed; that is, it was free to change naturally after the onset of the cold pressor task. Participants were instructed to keep their hands inside the cold water as long as they could tolerate it. Although participants were not explicitly instructed to avoid moving their hands in the cold water bucket, they kept their hands relatively stable throughout the task. The entire cold pressor task was video recorded and the duration that each participant kept their hands in the cold water was quantified via a chronometer as the measure of the pain tolerance of that participant. If the participant did not withdraw their hands within five minutes, the experimenter instructed the participant that they must remove their hands from the cold water. This upper limit was established due to ethical considerations, as exposure to cold water for an unlimited amount of time could potentially cause tissue damage and other related complications. The pain tolerance of these participants was recorded as 300 s. At the end of the cold pressor task, the participants were asked to place their hands in the tepid water bucket as long as they felt comfortable that their hands were sufficiently warm. All parameters reported above were determined based on the relevant literature, using onset hand temperatures within the 25–40 °C range and cold water temperatures within the 0–5 °C[13,21,25,26], and pilot testing of our system.

Procedure

Participants were randomly assigned to one of the four groups: silence, music, music-and-attention-to-music (MAM), and music-and-attention-to-pain (MAP, Fig. 1a). While the participant was reading and signing the informed consent in a room different than the experimental room, the experimenter prepared the experimental room by ensuring that the initial temperature of the cold water was within the desired levels. Before the participant entered the experimental room, the experimenter started the music playback in the experimental room for participants in the music, MAM, and MAP groups. When the participant entered the experimental room, the cold pressor task procedure as described above was employed to measure the participant's pain tolerance level. The additional procedures were different based on the group assignment of the participants.

Participants in the silence group were administered the cold pressor task as described above with no additional procedures. For participants in the music group, Mozart's composition was played back during the entire time the participant spent in the experimental room, but no other additional procedures or instructions were administered. For participants in the MAM and MAP groups, the same musical piece was also played back during the entire time the participant was in the experimental room, but there were additional procedures. Participants in the MAM group were instructed to attend to the arousal levels of the musical piece throughout the entire cold pressor task and verbally report them on an 11-point scale (0 = very relaxing, 10 = very arousing) every five seconds from the time they placed their hands into until they withdrew their hands from the cold water bucket. Participants in the MAP group were instructed to attend to their own pain levels throughout the entire cold pressor task and, similarly, verbally report them on an 11-point scale (0 = no pain, 10 = worst possible pain) every five seconds. In both groups, verbal ratings of the participant were elicited by the verbal instruction of the experimenter, who was positioned in the back corner of the room behind the participant, every five seconds from the beginning to the end of the cold pressor task.

At the end of the cold pressor task, all participants were asked to leave the experimental room and go to the initial room where they signed the informed consent form. All participants were asked to complete the Turkish version of the Positive and Negative Affect Schedule[39,40] (PANAS) and a demographic form. Additionally, participants in the music, MAM, and MAP groups were asked to rate the music that they have heard on an 11-point scale in terms of liking (0 = did not like it at all, 10 = liked it a lot), valence (0 = very negative, 10 = very positive), and arousal (0 = very relaxing, 10 = very arousing).

Data analysis

Data was prepared for analyses using MATLAB (version R2023b) and analyzed in JASP[41] (version 0.16.4). The great majority of our variables were non-normally distributed as indicated by significant Shapiro-Wilks tests; thus, as a general approach, we used non-parametric statistical tests for our analyses. Specifically, when comparing a sample of values to a reference value, we used the Wilcoxon signed-rank test; when comparing two groups to each other, we used the Mann-Whitney U test; when comparing multiple groups with each other, we used the Kruskal-Wallis test; and for correlation analyses, we used the Kendall's Tau correlation. For all analyses, the alpha value for statistical significance was set to 0.05 and Bonferroni corrected for multiple comparisons as indicated specifically for each analysis in the *Results* section.

We included a number of control variable measurements to ensure the equivalence of our experimental groups in critical parameters. The temperatures of participants' hands at the beginning of the cold pressor task, as well as the temperatures of the tepid water and cold water, were measured via thermometers as explained above. The weather temperature was also included as reported at www.wunderground.com for the day and the time during which the experiment was conducted (mean ± sd = 11.4 ± 3.2 °C, min-max = 2.8–16.1 °C). Positive and negative PANAS scores were calculated separately by taking the average of the corresponding items. In addition, music liking, valence, and arousal ratings collected at the end of the experiment from all the groups except the silence group, and the reported genders and ages from all groups were taken into account as control variables.

We also conducted a number of manipulation check analyses. For the MAP group, we wanted to verify that participants indeed attended to and reported their experienced pain levels during the cold pressor task. Nevertheless, since we did not have an independent and objective measure of how much pain the participants experienced throughout the task, we assessed the internal consistency of the pain ratings by testing whether each participant's time-resolved pain ratings during the task correlated with the average time-resolved pain ratings of all the other participants. If the participants were to not attend to their experienced pain levels and just report random ratings, then we would expect the correlations between the temporal profiles of ratings to be around zero on average. However, if they indeed report their experienced pain levels as time goes on in the cold pressor task, the temporal profiles would be expected to be positively correlated with each other. Thus, for each participant, we calculated the correlation coefficient between the time-resolved pain ratings of that participant and the average time-resolved pain ratings of all the other participants. Then, we tested whether these correlation coefficients were significantly greater than zero at the group level. We also tested whether the proportion of participants with significant positive or negative correlation coefficients in the group exceeded the proportions that would be expected by chance via Binomial tests.

For the MAM group, we checked whether each participant's time-resolved arousal ratings correlated with the average time-resolved ratings of an independent validation sample. First, the internal consistency of the validation sample was assessed exactly as described above for pain ratings. We then calculated the correlation coefficient between the time-varying arousal ratings of each participant in the MAM group and the average time-varying normative arousal ratings to assess whether the participants indeed rated the arousal level of the music as instructed. We examined these correlation coefficients at the group and the individual level as described for above for pain ratings. Note that these analyses were conducted on 28, instead of 30 participants, since it was not possible to calculate correlation coefficients for two participants. One participant in the MAM group kept their hands in the cold water for only 9 s, providing only one arousal rating during the cold pressor task. It was thus not possible to calculate a correlation coefficient for that participant. Another participant's video recording was corrupted, not allowing us to decode the period of the music piece to which they were exposed during the cold pressor task. Thus, it was not possible to correlate their arousal ratings with the time-matching normative arousal ratings.

Data availability

The data that support the findings of this study are openly available at Open Science Framework (https://osf.io/ntvf7/).

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Author contributions
Conceptualization: NBA, ES; Data Curation: NBA; Formal Analysis: NBA, ES; Investigation: NBA; Methodology: NBA, ES; Project Administration: ES; Resources: ES; Software: NBA, ES; Supervision: ES; Validation: ES; Visualization: NBA, ES; Writing – Original Draft and Preparation: NBA; Writing – Review and Editing: NBA, ES.

Declarations

Competing interests
The authors declare no competing interests.

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