Bringing WALL-E out of the Silver Screen: Understanding How Transformative Robot Sound Affects Human Perception

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***Abstract*— Lovable robots in movies regularly beep, chirp, and whirr, yet robots in the real world rarely deploy such sounds. Despite preliminary work supporting the perceptual and objective benefits of intentionally-produced robot sound, relatively little research is ongoing in this area. In this paper, we systematically evaluate transformative robot sound across multiple robot archetypes and behaviors. We conducted a series of five online video-based surveys, each with $N \approx 100$ participants, to better understand the effects of musician-designed transformative sounds on perceptions of personal, service, and industrial robots. Participants rated robot videos with transformative sound as significantly happier, warmer, and more competent in all five studies, as more energetic in four studies, and as less discomforting in one study. Overall, results confirmed that transformative sounds consistently improve subjective ratings but may convey affect contrary to the intent of affective robot behaviors. In future work, we will investigate the repeatability of these results through in-person studies and develop methods to automatically generate transformative robot sound. This work may benefit researchers and designers who aim to make robots more favorable to human users.**

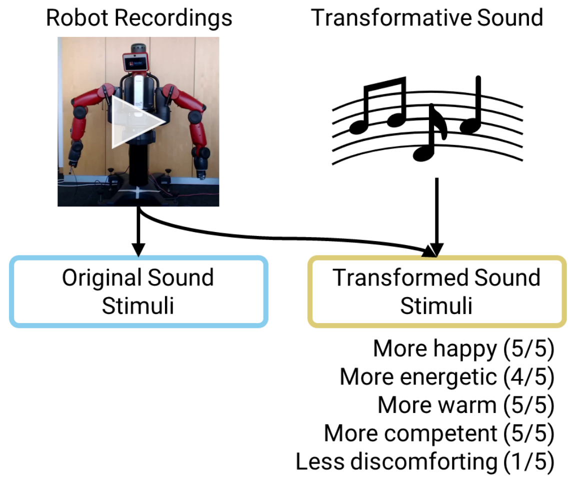

Fig. 1: An overview of the study manipulation and results.

I. Introduction

Beloved and well known robots in the media such as Rosie [1], R2-D2 [2], and WALL-E [3] all use transformative sound to communicate with others. But where is this type of interaction when it comes to robots in the real world? Past works have begun to investigate the effects of transformative sound—non-linguistic sound intentionally added to a robot to complement its regular sonic profile—but little is definitively known about the effects of transformative sound across robot archetypes and use cases. Accordingly, robots that employ transformative sound remain rare and little guidance exists to help roboticists emulate the sound design of cinematic robots. In this paper, *we aim to better understand of the effects of transformative sound in human-robot interaction (HRI).*

Past research shows that transformative sound may benefit human-robot collaboration (HRC) and perceptions of robots. In [4], adding music to a robot helped to mask an undesirable sound and led to improved subjective ratings of the robot. Adding broadband and tonal sound to an out-of-sight robot also helped human collaborators localize and notice the robot [5]. Other work showed that intentionally varying the sound associated with a robot's motion can improve perceptions and understanding of the robot's behavior [6], [7]. While these initial works establish the potential benefits of transformative sound, *our work explores the generalizability of transformative sound effects across robot type, sound profile, and use case*.

Our central goals in this paper are to understand (1) whether transformative sound improves participant perceptions of video recordings of robots and (2) whether this effect persists across robot applications. We reviewed related work from the robot sound and entertainment fields in Section II before developing transformative sounds for five robots and a central study design in Section III. Section IV presents the five studies' results, which show the consistent benefits summarized in Fig. 1. We discuss these results, design implications, strengths, limitations, and future work for the under-explored field of robot sound in Section V.

II. Related Work

To inform our investigation, we explored prior work in both *consequential sound* (e.g., the meshing of servo motor gears, the hum of cooling fans, or the rattling of wheels) and *transformative sound* (e.g., non-linguistic utterances, beeping from a back-up alarm, or movement-synchronized music) from robots [8]. While this paper focuses on transformative robot sound, research from both topics guided our work.

Recent work has shown that consequential sound can detract from perceptual ratings of robot arms [9]. In another study, participants perceived differences between servo sounds and correctly labeled the lowest-quality and least expensive servo as the most inappropriate, untrustworthy, weak, imprecise, and inexpensive [10]. However, only one of the six subjective attribute scales correlated with any objective servo specifications [11]. A study on a humanoid robot found

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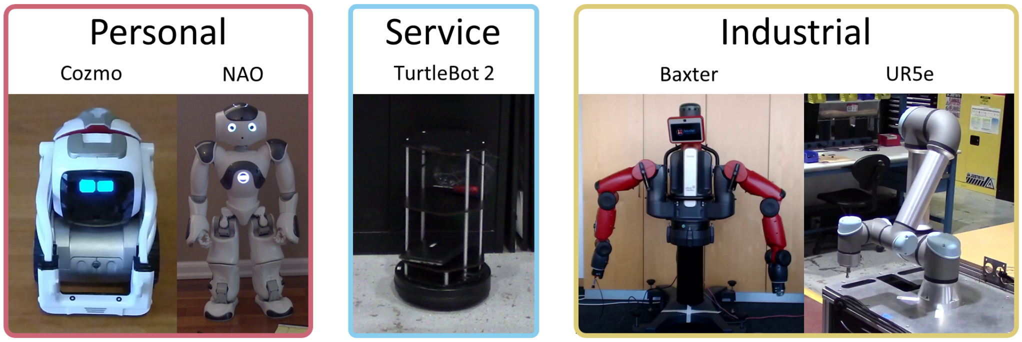

Fig. 2: Cropped images of the five robots investigated in our series of video studies.

that consequential robot sound may communicate emotions against the intent of corresponding motions [12]. Consequential robot sound does affect participant perceptions, but functional requirements and available components limit the range of feasible consequential sound. Comparatively, transformative sound offers greater design freedom.

Transformative robot sound research has examined several subtypes of sound, including *musical* and *vocable* sound. Generally, transformative sound is designed to be associated with robot function and motion. Robots in the media often employ transformative sounds; famous examples include the beeps of Rosie the robot [1], the analog synthesized sounds of R2-D2 [2], and the emotive vocable sounds of WALL-E [3]. This type of sound can help robots in the real world to succeed as well. Musical transformative sound has the potential to ameliorate negative impressions due to a robot's consequential sound; added music masked undesirable sounds and led participants to rate a robot more highly on seven subjective scales [4]. Vocable sounds (also known as non-linguistic utterances) convey affect both independently and in support of other affective robot actions by helping to amplify their affective interpretation [13], [14].

Transformative sound can improve perceptual and objective measures in HRI. Work on human localization of visually obscured robots showed that adding broadband and tonal noise increased accuracy, inference speed, perceived noticeability, and perceived localizability, though at the cost of increased annoyance [5]. Additionally, the design of transformative sound impacts its reception. In a study where robots approached participants, transformative sound that scaled in volume with the velocity of the robot performed better than a constant transformative sound on five subjective scales [6], [7]. In this paper, we build on past work by *exploring the effects of adding transformative sound to a representative range of robots and behaviors*.

III. Methods

We conducted a series of five video-based studies via Amazon Mechanical Turk (MTurk) to explore the effect of transformative sound on participants' perceptions of varying behaviors for five different robots.

A. Hypotheses

Past work shows that lowering consequential robot sound improves perceptions of robots [9], but for most robots, eliminating (or even reducing) consequential sound is not feasible. A promising alternative is applying transformative sound, which has improved perceptions of robots in individual domains [4], [6], [7]. Our hypothesis focuses on whether this concept is reproducible across robot types and actions:

H1: Adding transformative sound will lead to improved perceptions of robot valence, energy level, warmth, competence, and comfort across all domains.

B. Study Design

Based on availability and range of uses, we selected the following commonly used personal, service, and industrial robots for our studies: the Cozmo, NAO, TurtleBot 2, Baxter, and UR5e. Figure 2 shows each robot and its associated categorization. The breadth of selected robots enabled the study of the effects of transformative sound across differing behavior types (i.e., social and asocial), robot form factors, inherent consequential sounds, and motions.

Each of the five studies involved one robot. In each study, we recorded the designated robot performing a set of four behaviors typical for that platform. These sets of behaviors served as a repetition and helped us investigate trends across different use contexts and motions. To help support the idea that the study involved different robots (one with and one without transformative sound), we recorded two sets of the robot videos with slightly different backgrounds. We added transformative sound to one set of videos.

Using these stimuli, we developed a within-subjects study design in which participants would evaluate all eight stimuli involved in a given study. This design included two factors: *sound condition* (two levels: original and transformed) and *robot behavior* (four levels: A, B, C, and D). We then implemented the design in Qualtrics surveys for MTurk workers. Workers responding to the surveys were from the United States and had >97% prior task approval rate and >5000 previously approved tasks. Each worker could participate in a maximum of one survey. Online survey studies allowed us to compare many stimuli with sample sizes of $N \approx 100$ for sufficient statistical power.

C. Sound Design

Study 1, which employed Cozmo, used robot behaviors with and without developer-provided sounds [15]. Including one stimulus set of this type allowed for comparison between the effects of professionally developed transformative sound and sounds created by the authors for the studies.

For each robot other than Cozmo, we developed a set of transformative sounds to overlay onto recordings based on past examples from research and the media (further described in Section II). Using a digital audio workstation (DAW), we added tonal and broadband sounds to complement the existing sonic profile of each robot. The method for creating each robot's transformative sound varied, so we made the study stimuli available for direct consideration in [16] and in the video included with this paper.

D. Procedure

Participants who enrolled in the study provided informed consent and then continued to a 15-minute survey. The start of the survey was identical across all studies and included a loudness calibration video, an introduction to the robot in the study, and a practice stimulus of the Cassie robot with the post-stimulus questionnaire described in Section III-E.

Next, participants completed the robot-specific module, which included eight stimulus videos: four with original sound and four with original plus transformative sound. Each stimulus was followed by the same post-stimulus questionnaire mentioned previously. Stimuli appeared in a semi-random order so that participants would never see the original and transformed versions of a given video adjacent to one another. After the fourth and eighth stimulus presentations, participants had to successfully complete an attention check question to continue.

The final part of the survey included a free-response question for gathering more information about what influenced participant responses and a manipulation check question to confirm that respondents could discern between a video with and without added transformative sound. Lastly, participants completed the attitudes and demographic questionnaires also described in Section III-E. Participants were compensated with USD 3.75 for completing the survey. Participants who did not finish the survey, failed attention or manipulation checks, or attempted to take the survey more than once were excluded from the study.

E. Measures

The surveys included the following measurement groups:

Post-stimulus questionnaire: after each stimulus, the Robotic Social Attributes Scale (RoSAS) captured participant perceptions of the robot in terms of *warmth*, *competence*, and *discomfort* by averaging six component attribute responses each [17]. Using a six-point Likert scale, participants rated how much the robot was or was not associated with each attribute. The attribute of "happy," a component of *warmth*, and an additional attribute of "energetic" captured perceptions of the robot's *valence* and *energy level* (arousal) from the circumplex model of affect [18].

Free-response question: after evaluating all stimuli, participants described the most important factors behind their responses with a minimum of 200 characters.

Attitudes questionnaire: after the free-response question, the Negative Attitudes Towards Robots Scale (NARS) captured general attitudes towards robots. On a seven-point Likert scale, participants indicated how much they agreed or disagreed with fourteen statements. The results were then averaged to measure participants' negative attitudes towards *interactions with robots*, *social influence of robots*, and *emotions in robots* [19].

Demographic questionnaire: lastly, several questions recorded demographic and occupational information.

F. Analysis

We analyzed post-stimulus questionnaire responses using repeated-measures analysis of variance (rANOVA) tests with a Greenhouse-Geisser sphericity correction and an $\alpha = 0.05$. Each 2×4 rANOVA used factors of *sound condition* and *robot behavior*. For rANOVAs that indicated a significant effect due to *sound condition*, we applied post-hoc pairwise comparisons with the Holm-Bonferroni correction for Type I errors to determine whether the responses to the sound condition differed in each of the four *robot behavior* levels. We reported effect sizes using η^2_G [20], comparable to η^2, where $\eta^2 = 0.010$ is considered a small effect, $\eta^2 = 0.040$ a medium effect, and $\eta^2 = 0.090$ a large effect [21].

For all studies, responses to the common introductory stimulus and to the attitudes questionnaire were analyzed using a one-way analysis of variance (ANOVA) test. This analysis helped to determine whether perceptions of stimuli and attitudes towards robots were similar across studies.

All analyses were completed using jamovi 1.6 [22]–[25].

IV. Results

A. Study 1 Results: Cozmo

Participants: $N = 100$ adults between 22 and 80 years of age ($M = 36.8$, $SD = 10.3$) completed Study 1, including 63 cisgender men, 36 cisgender women, and 1 transgender woman. 42 participants reported an educational or occupational background in science, technology, engineering or mathematics (STEM), and 16 participants reported a background in music.

Post-Stimulus Questionnaire Responses: rANOVAs indicated that transformative sound correlated with significantly higher *valence* ($p < 0.001$, $F(1, 99) = 41.45$, $\eta^2_G = 0.031$), *energy level* ($p < 0.001$, $F(1, 99) = 55.61$, $\eta^2_G = 0.050$), *warmth* ($p < 0.001$, $F(1, 99) = 101.89$, $\eta^2_G = 0.036$), and *competence* ($p < 0.001$, $F(1, 99) = 41.53$, $\eta^2_G = 0.012$). Differences in perceived *discomfort* were not significant. Figure 3 shows the distribution of responses for measures that yielded a significant difference between *sound conditions* and the results of post-hoc pairwise analysis.

According to the post-hoc analysis, transformative sound improved measures in most pairwise comparisons as well. One exception was the expected decrease in valence for Behavior C, which expressed "arguing." Overall, adding transformative sound produced a strong and consistent improvement in valence, energy level, warmth, and competence.

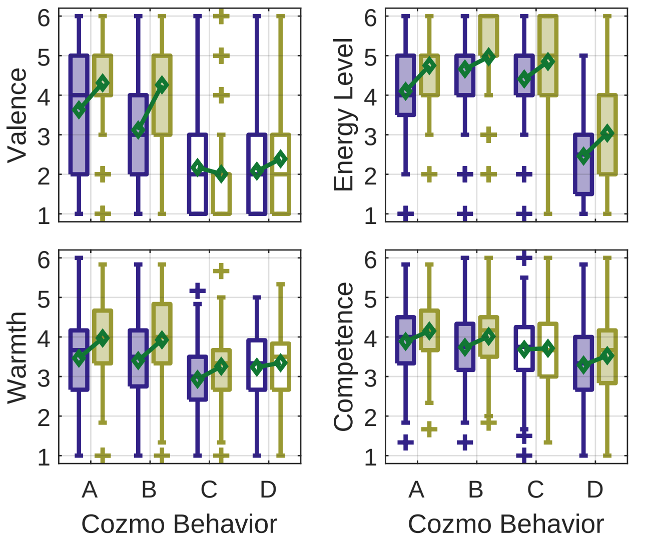

Fig. 3: Results of post-stimulus responses that yielded significant differences due to *sound condition* for Study 1. Boxplots include boxes from the 25th to the 75th percentiles, whiskers up to 1.5 times the inter-quartile range, and "+" marks to indicate outliers. *Original sound* stimuli responses in blue boxplots are placed to the left and *transformed sound* stimuli responses in yellow boxplots are placed to the right of each *robot behavior* gridline. Boxplot pairs that are filled in indicate significant differences. Green lines connect the means of each boxplot pair.

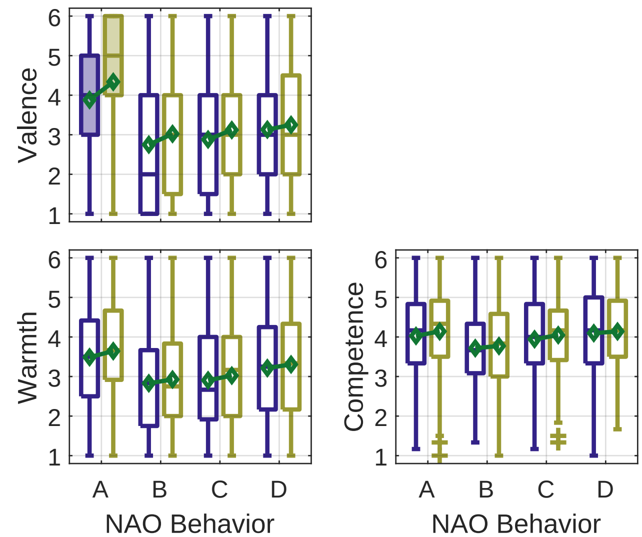

Fig. 4: Results of post-stimulus responses that yielded significant differences due to *sound condition* for Study 2.

B. Study 2 Results: NAO

Participants: $N = 92$ adults between 23 and 71 years of age ($M = 37.8$, $SD = 10.1$) completed Study 2. Participants were composed of 53 cisgender men, 38 cisgender women, and 1 transgender man. 37 participants had a STEM background, and 16 participants had a music background.

Post-Stimulus Questionnaire Responses: rANOVAs indicated that transformative sound correlated with significantly higher *valence* ($p < 0.001$, $F(1, 91) = 20.13$, $\eta^2_G = 0.008$), *warmth* ($p = 0.001$, $F(1, 91) = 11.22$, $\eta^2_G = 0.002$), and *competence* ($p = 0.033$, $F(1, 91) = 4.66$, $\eta^2_G = 0.001$). Differences in perceived *energy level* and *discomfort* were not significant. Figure 4 shows the distribution of responses for measures that yielded a significant difference between *sound conditions* and the results of post-hoc pairwise analysis.

Post-hoc analysis showed that transformative sound significantly improved measures in one pairwise comparison. Ratings tended to increase for all other shown pairs. Transformative sound produced a smaller but consistent improvement in valence, warmth, and competence.

C. Study 3 Results: TurtleBot 2

Participants: $N = 94$ adults between 23 and 64 years of age ($M = 37.6$, $SD = 9.9$) completed Study 3, including 58 cisgender men and 36 cisgender women. 45 participants had a STEM background, and 22 had a music background.

Post-Stimulus Questionnaire Responses: rANOVAs indicated that transformative sound correlated with significantly higher *valence* ($p < 0.001$, $F(1, 93) = 46.07$, $\eta^2_G = 0.061$), *energy level* ($p < 0.001$, $F(1, 93) = 48.42$, $\eta^2_G = 0.031$), *warmth* ($p < 0.001$, $F(1, 93) = 38.15$, $\eta^2_G = 0.021$), and *competence* ($p < 0.001$, $F(1, 93) = 20.89$, $\eta^2_G = 0.007$). Differences in perceived *discomfort* were not significant. Figure 5 shows the distribution of responses for measures that yielded a significant difference between *sound conditions* and the results of post-hoc pairwise analysis.

Post-hoc analysis showed that transformative sound significantly increased ratings in all pairwise comparisons for valence, energy level, and warmth. One competence rating increased significantly, and the rest tended to improve. Transformative sound led to a strong and consistent improvement in valence, energy level, warmth, and competence.

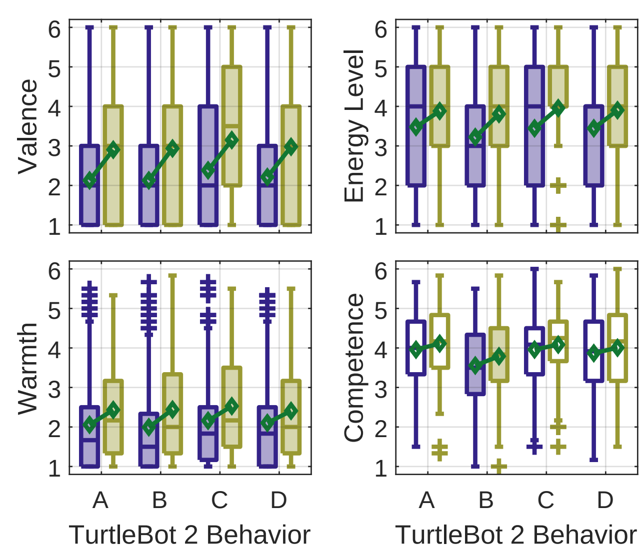

Fig. 5: Results of post-stimulus responses that yielded significant differences due to *sound condition* for Study 3.

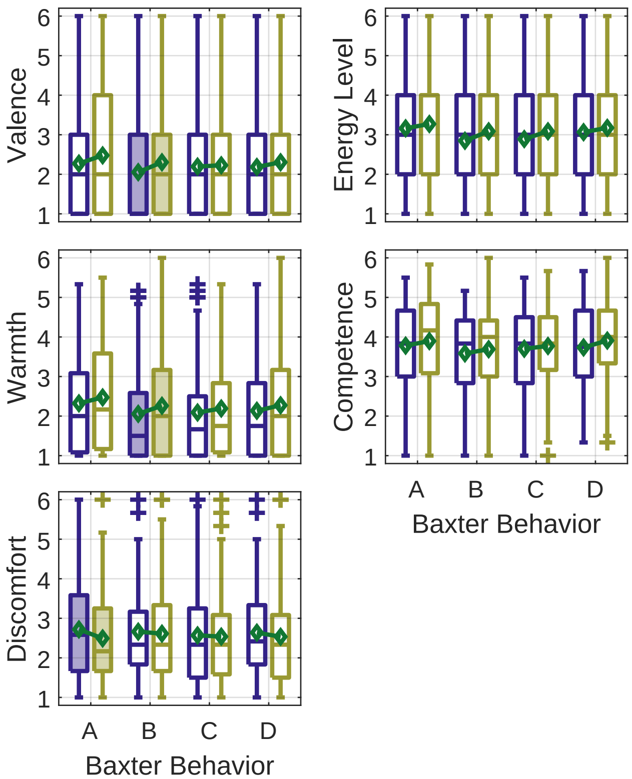

Fig. 6: Results of post-stimulus responses that yielded significant differences due to *sound condition* for Study 4.

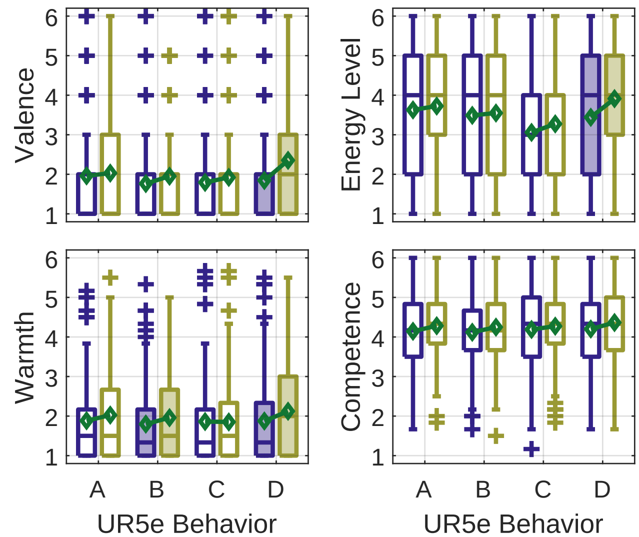

Fig. 7: Results of post-stimuli responses that yielded significant differences due to *sound condition* for Study 5.

D. Study 4 Results: Baxter

Participants: $N = 92$ adults between 20 and 67 years of age ($M = 37.3$, $SD = 10.5$) completed Study 4, including 52 cisgender men, 38 cisgender women, 1 transgender man, and 1 transgender woman. 49 participants had a STEM background, and 28 participants reported a music background.

Post-Stimulus Questionnaire Responses: rANOVAs indicated that transformative sound correlated with significantly higher *valence* ($p = 0.007$, $F(1, 91) = 7.72$, $\eta^2_G = 0.003$), *energy level* ($p = 0.004$, $F(1, 91) = 8.54$, $\eta^2_G = 0.003$), *warmth* ($p < 0.001$, $F(1, 91) = 16.04$, $\eta^2_G = 0.003$), and *competence* ($p = 0.003$, $F(1, 91) = 9.37$, $\eta^2_G = 0.003$), as well as significantly lower *discomfort* ($p = 0.013$, $F(1, 91) = 6.49$, $\eta^2_G = 0.002$). Figure 6 shows response distributions for measures with a significant difference between *sound conditions* and the post-hoc analysis results.

According to the post-hoc analysis, transformative sound significantly improved robot perception for three pairwise comparisons. Ratings tended to decrease for all discomfort pairs and increase for all other ratings. Adding transformative sound produced a smaller but consistent improvement in valence, energy level, warmth, competence, and discomfort.

E. Study 5 Results: UR5e

Participants: $N = 102$ adults between 23 and 67 years of age ($M = 39.1$, $SD = 10.0$) completed Study 5. Participants included 51 cisgender women, 50 cisgender men, and 1 non-binary individual. 47 participants had a STEM background, and 17 participants reported a music background.

Post-Stimulus Questionnaire Responses: rANOVAs indicated that transformative sound correlated with significantly higher *valence* ($p < 0.001$, $F(1, 101) = 13.81$, $\eta^2_G = 0.007$), *energy level* ($p = 0.005$, $F(1, 101) = 8.44$, $\eta^2_G = 0.005$), *warmth* ($p < 0.001$, $F(1, 101) = 13.14$, $\eta^2_G = 0.004$), and *competence* ($p = 0.001$, $F(1, 101) = 10.95$, $\eta^2_G = 0.005$). Differences in perceived *discomfort* were not significant. Figure 7 shows the distribution of responses for measures that yielded a significant difference between *sound conditions* and the results of post-hoc pairwise analysis.

Post-hoc analysis showed that transformative sound significantly improved measures in several pairwise comparisons. Ratings tended to increase for all other shown pairs. Overall, transformative sound produced a smaller but consistent improvement in valence, energy level, warmth, and competence.

F. Across Study Results

One-way ANOVAs indicated no significant differences between studies for the common introductory stimulus post-stimulus questionnaire and the attitudes questionnaire results. Overall, participants rated the common introductory stimulus for *valence* ($M = 2.16$, $SD = 1.38$), *energy level* ($M = 3.86$, $SD = 1.36$), *warmth* ($M = 2.03$, $SD = 1.15$), *competence* ($M = 3.60$, $SD = 0.96$), and *discomfort* ($M = 3.03$, $SD = 1.07$), and also expressed neutral to somewhat positive attitudes towards *interactions with robots* ($M = 2.97$, $SD = 1.39$), *social influence of robots* ($M = 3.88$, $SD = 1.37$), and *emotions in robots* ($M = 3.76$, $SD = 1.41$). Participant similarities allow us to safely compare the results across studies.

V. Discussion

Results partially supported **H1**. Significant increases in *valence*, *warmth*, and *competence* in transformed sound conditions for all five studies strongly fulfilled the hypothesis. *Energy level* also increased in four studies, partially supporting the hypothesis. These results reinforce past findings in [4],

[7], though different measures and reporting methods prevent a more direct comparison. Lastly, *discomfort* decreased in only one study. While a lack of reduction in discomfort did not support the hypothesis, the results showed that the transformed sounds from our studies performed better than sounds in [5], where all studied transformative sounds increased perceived annoyance. Overall, *transformative sound increases valence, energy level, warmth, and competence*.

Free-response entries help to support and explain these results. Participants remarked that *"I had a warmer feeling to the [TurtleBot 2] when he would come through making the 'boop beep boop' noises"* and that *"sounds associated with the [NAO] gave them some personality,"* Other responses described how the sounds affected their comfort, writing *"[i]f it was just a mechanic whirling sound, it was much more intimidating then the happy little beeps"* for the UR5e and *"I can imagine my mother or grandmother feeling more comfortable around [Baxter] robots that make sounds before moving."* Some participants mentioned cultural references, such as one respondent who wrote *"[the TurtleBot2] made happy little sounds like the R2D2 robot."* While responses did not always include sound as the primary influencing factor, *participants overall described robots with transformative sound positively* with adjectives such as *"charming," "friendly," "human-like," "capable,"* and *"interactive."*

While overall rANOVA results indicated significant differences, variable effect sizes and numbers of significant pairwise comparisons show that the transformed sounds had unequal levels of effectiveness. As expected, the commercially developed transformative sound for Cozmo performed successfully. Promisingly, the musician-designed sound for the TurtleBot 2 performed similarly well. Transformative sound in the three remaining studies produced significant results but smaller effect sizes, indicating potential for further sound design improvement. Thus, *current transformative sound designers may need to follow the design-build-test cycle of human-centered design to achieve successful results.*

A. Design Implications

These results develop two themes for robot design and robot sound research: (1) *adding transformative sound can improve user perceptions* and (2) *the suitability of transformative sounds influences how effective the sounds will be*. After finding similar results across all five studies, we are confident that the perceptual improvements of transformative sound will generalize to other robots. Follow-up in-person studies for these and additional robots would help to verify and reinforce the conclusions of this work.

For roboticists, we recommend adding transformative sound to robots to increase their appeal with human users. While prior work in consequential sound indicates that reducing loudness may improve user perceptions [9], functional requirements may preclude making robots quieter. In such cases, transformative sound offers a method to maintain or increase sound intensity and still improve robot perceptions. Roboticists may find the best results by collaborating with music and sound design experts. Parallel to our work, [26] detailed design methods for developing transformative sound.

As designing suitable transformative sound for different scenarios still presents a significant challenge, one important task for those working in robot sound is to create software and hardware tools to support easier implementation of transformative robot sound. In future work, we plan to continue collaborating with music and sound design experts to (1) identify a toolkit of free software and methods that roboticists can use to create transformative sound and (2) propose methods for generating transformative robot sound based on factors like consequential sounds emergent from the robot, robot behaviors, and environmental factors.

B. Key Strengths and Limitations

One strength of this work is our collaboration with sound designers (i.e., our coauthors from the performing arts and music fields) to create transformative sounds. This partnership with experienced sound designers may be one reason why our results are promising and generalizable across robots and applications. Because of the online nature of the study, we were able to quickly iterate over multiple robot platforms and evaluate our research questions in a wider variety of domains than past work in this space. This process of testing repeatability across robots/domains is key to pushing the use of transformative sound to the next level.

A major limitation of this work is that online video-based studies cannot fully represent in-person interactions with robots. Accordingly, we will conduct in-person follow-up studies to confirm that the findings are reproducible in the real world. The participant group is also not representative of all robot users, and the cultural context of these results is most relevant to the United States. We plan to deliberately recruit more diverse participant groups in future work.

C. Conclusions

In this work, we investigated the effects of vocable and transformative sound by creating sounds for five different robots and conducting an online study for each. A consistent two-factor within-subjects design allowed us to improve on past work by analyzing the repeatability of effects across robotic platforms and applications. The results showed that transformative sound leads to improved perceptions of robots. Unexpectedly, transformative sounds also almost always increased valence and energy level ratings. This work and the example stimuli included can help guide robot sound designers and motivate robotics researchers to develop automated transformative sound systems for future robots.

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