Infrasound for HRI: A Robot Using Low-Frequency Vibrations to Impact How People Perceive its Actions

Raquel Thiessen, Diljot S. Garcha, Daniel J. Rea, Cheng Cheng, James E. Young
Department of Computer Science, University of Manitoba
{thiess83, garchads, daniel.rea, chengc35, young}@cs.umanitoba.ca

Abstract—**We investigate robots using infrasound, low-frequency vibrational energy at or near the human hearing threshold, as an interaction tool for working with people. Research in psychology suggests that the presence of infrasound can impact a person's emotional state and mood, even when the person is not acutely aware of the infrasound. Although often not noticed, infrasound is commonly present in many situations including factories, airports, or near motor vehicles. Further, a robot itself can produce infrasound. Thus, we examine if infrasound may impact how people interpret a robot's social communication: if the presence of infrasound makes a robot seem more or less happy, energetic, etc., as a result of impacting a person's mood. We present the results from a series of experiments that investigate how people rate a social robot's emotionally-charged gestures, and how varied levels and sources of infrasound impact these ratings. Our results show that infrasound does have a psychological effect on the person's perception of the robot's behaviors, supporting this as a technique that a robot can use as part of its interaction design toolkit. We further provide a comparison of infrasound generation methods.**

Keywords— Social HRI, Infrasound, Sonic Interaction

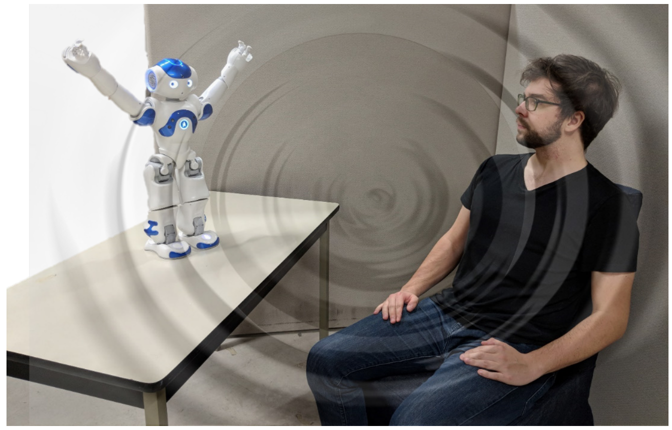

Fig. 1. We demonstrate that a robot can use infrasound – vibrational energy near the lower frequency threshold of human hearing – to effect how interactions are perceived.

I. Introduction

As robots start to integrate into people's everyday worlds, social robots are emerging that use human or animal-like language to facilitate interaction. Social robots leverage anthropomorphism, the phenomenon where people attribute inanimate objects with lifelike qualities, intentions, emotions, and so forth, to support interaction. In addition to social communication being easy to understand [1], because of anthropomorphism people can empathize with robots [2], robots can persuade people [3] and can be effective for therapy (similar to pets) [4]. Effective social robot design must consider how a robot integrates socially and impacts people's moods. As such, an ongoing theme of research is to develop interaction vocabulary and toolkits to help HRI practitioners in designing social and emotional interactions. In this paper we present a novel tool for social robots: infrasound.

By definition, infrasound is vibrational energy at or near the threshold of human hearing [5]. Infrasound has been a topic of inquiry regarding human psychology since the 1960s [6], [7], and garnered attention following a 1998 paper suggesting a link between infrasound and ghost sightings [8]. The paper detailed how naturally-occurring infrasound standing waves in a room could create feelings of discomfort and depression, and resonances can cause physical phenomena: in this case, a sword vibrating and "gray blob" optical illusions [8]. A follow-up experiment hosted concerts with, in some conditions, music laced with a 17hz infrasound tone, and explored psychological impact on listeners; infrasound heightened listener emotional response and created more "strange experiences," and increased anxiety [9], [10]. However, this work was not peer reviewed, and a recent review of infrasound literature highlighted mixed results: psychology does not yet have a definitive understanding of the impacts of infrasound [6]. In this work, we extend the inquiry of using infrasound to impact listener psychology by exploring its use by social robots.

We conducted a series of exploratory experiments that investigate how the presence of infrasound may alter how people perceive a social robot's affective gestures (Fig. 1). Our results indicate that the presence of infrasound makes a robot's motions appear more energetic and happier. Further, we found no impact of infrasound generation method (through-air vs. contact vibration), suggesting versatility of implementation. Given that large robots likely already produce infrasound, or may work in environments (e.g., factories) with levels of infrasound, our results highlight the importance of considering how infrasound will impact how a robot is perceived. Further, this suggests that robots can use infrasound when interacting with people; for example a factory robot could use a speaker, or vibration motors, to impact how it is perceived.

II. Related Work

Much of social HRI work is framed as a robot mapping a communication goal to interaction (e.g., motion intention in gaze [11], system state as emotion [1]), with a person expected to notice and interpret the social signal. However, there is also subtler work, such as a robot using whispering to develop a sense of intimacy [12], where people may not be expected to suspect the true purpose of the interaction.

Examples can get complex, for example, as with a robot that makes eye contact with a person, for the purpose of a third party noticing the eye contact. Here, the robot uses its gaze to shape the third party's interactions [13]. Similarly, a robot can shape relationships between two people by altering its own relationships with those people (e.g. taking sides in a discussion between the other two), leveraging social theories [14]. Our work extends this direction, where we investigate how robots can use infrasound subtly to shape interaction, with people likely not being not aware of the technique.

Designing robot behaviors to shape users' mood, behavior, or impressions of the robot, is a wide area of study. Persuasive robotics employs social norms and leverages expectations, such as by placing a robot in a position of authority to impact interaction [3], [15]. Robots can use empathy to purposefully make people feel bad [2] and attempt to change their behavior [16]. In teamwork scenarios, a robot can use social techniques to mitigate teamwork issues in an attempt to shape opinions of others [17]. However, we note that such techniques are leveraging inherent properties of social interaction; our work in infrasound take a fundamentally different approach, where the actual underlying mechanism is not yet well understood.

The field of sonic interaction design specifically investigates the use of sound in human-computer interaction [18]. In addition to simple alerts, sound has been investigated for a range of uses including peripheral awareness [19] or to shape aesthetics. For example, automobile teams include acoustical engineers who design the sound of a car (e.g., how a door sounds when closed) to improve satisfaction [20]. Vibration has further been widely explored as a communication channel in tangible computing (e.g., [21]). This includes work with robots (e.g., [22]), such as how a robot arm's motor sound can shape people's perceptions of the arm's competence and their trust toward it [23]. A similar project showed how servo motor sound can be altered to communicate a range of affect [24]. Musical rhythm can be used for encouraging engagement with robots and for therapeutic purposes [25]. We continue this body of work by explicitly investigating how robots can use infrasound to impact the person's psychological mood and, by proxy, their perceptions of the robot. This paper contributes to the larger picture of investigating new tools and techniques that interaction designers can use to engineer and shape interaction with social robots.

III. Infrasound

Human perception of infrasound is complex. The lower hearing threshold varies between individuals, by age, and by context (e.g., what other noises are present) [26]. At lower frequencies sound can be sensed by various parts of the body, not only one's ears. Does infrasound only include *hearing* (with ears), or sensation? This is somewhat controversial. Sources typically list infrasound as starting from 16hz to 20hz [6], [27]. Practically, the exact threshold, and whether a vibration is sensed by ears or another part of the body, has been irrelevant, and *infrasound* is generally used to refer to vibrational energy near this threshold. For our paper we use infrasound in this sense.

Studies of infrasound have primarily focused on workplaces, where people can be exposed to high-amplitude infrasound for long periods of time, generated from heavy machinery [5], [28]. The very low frequencies of infrasound generate large wavelengths: for example, a 17hz tone has a wavelength of about 20m (at sea level, 20 degrees C). Thus infrasound travels large distances without being reflected or absorbed by obstacles [6] and is difficult to localize [29], [30], meaning a person can be impacted by infrasound even when far away from a source, and cannot easily tell from where the sound is originating.

A 2004 review found a range of effects on physiology, mood, and performance [31]. At the extreme, it can impact blood pressure and heart rate [32], cause balance disturbance, involuntary eye movement (nystagmus), and reduce awareness [33], with high level and medium-to-long exposure. In extreme cases (exposed to high volumes for long durations) participants report feeling "out of their body" [33]. Infrasound can impact concentration and cognitive performance, with participants noting vibration-sensation, pressure in their ears and inability to concentrate (exposure to a 7 HZ tone at a very loud 142 dBA [34]). At higher amplitudes, body resonant vibrations can occur in one's chest cavities, sinuses, and throat, with the most notable being chest resonance [28], [35], [36].

While we do not aim for such extreme results, we investigate how infrasound within health standards may influence a listener and impact how they perceive a robot's interactions.

IV. Infrasound Apparatus and Level

The core challenges in designing our experiment were the questions of how a robot could generate infrasound, and how loud the infrasound should be.

A. Infrasound Generation

Our exploration led to two methods for testing infrasound: through-the-air transmission using a speaker, or through-object transmission using a vibration motor. Prior work typically used large custom speakers [27] to generate infrasound, as standard commercial products often filter infrasound from amplification to protect equipment and for efficiency. However, modern commercial solutions are available without such limitations. We acknowledge that the through-the-air and through-object methods overlap: speakers cause resonance in objects, and vibrating objects cause the air to resonate. However, we focus on differences in the primary source of energy generation.

We wrote a program to generate infrasound. In all cases we generated a 17hz sinewave tone for our infrasound; this was selected based on prior infrasound work shown to have psychological effects on people [10]; we note that this was not scientifically validated itself, but falls within the well-studied rang of infrasound impacts on people. We included a fade-in and out feature to avoid an audible click associated with suddenly stopping (the high-frequency jump to 0 amplitude).

1) Through-the-air transmission using a speaker

Certain speakers can generate infrasound levels and frequencies commonly studied in analyses [5]. We purchased a consumer grade subwoofer that could generate infrasound tones. Further, we selected a sealed box design (no port hole for air flow), rated in provided specifications as producing purer low-frequency tones. We used the SVS SB-2000 500-watt (1,100-watt peak) subwoofer. We note that speaker placement with respect to a robot may not be important given that low frequencies are difficult for humans to localize [6].

Speakers used to generate infrasound are typically large and require a great deal of power. While feasible for a large robot (e.g., security sentry), we require a different solution for smaller humanoids, quadcopters, etc.

2) Through-object transmission using vibration motor

We experiment with transmitting infrasound to a person via object vibration, in this case the chair a person is sitting on, in comparison with through-the-air sources. While it does not generate the same sound pressure changes as a speaker would (hypothesized to influence humans [33]), this reduces health concerns. We selected a home-theater vibration motor (Buttkicker Low Frequency Effect Transducer) and amplifier (Dayton Audio SA1000 1000w) that does not filter low frequencies. We mounted the motor to the bottom of a chair, carefully concealed all wires leading to the chair (Fig. 2). As humans cannot localize low-frequency vibrations we do not expect them to notice the source at this location.

B. Calibration and Measurements

For our study it is important to measure and calibrate infrasound generation to ensure accuracy and consistency between participants, and to protect participant health; high amplitude sounds at low frequencies can damage hearing without causing discomfort, and so can go undetected unlike damage at higher frequencies [37]. Below we explain calibration, but provide specific levels in the study sections.

To measure our speaker, we used a factory-calibrated microphone (miniDSP UMIK-1) with unit-specific data loaded into open source software (Room EQ Wizard). This enabled us to measure absolute sound pressure levels independent of the microphone, computer, or software. We measured at expected ear height of the participant. To measure the vibration motor, we used an accelerometer in a commercial cell phone (Google Pixel One XL, "Vibration Analysis" app). We calibrated by placing the phone on top of the chair that the motor was mounted on.

C. Pilot: Infrasound Volume and Source

We conducted a pilot study to determine which infrasound source to use, and at what amplitude, for further study: it should be strong enough to induce psychological impact, but within health standards. Further, secondary resonant vibrations (at higher frequencies, e.g., chair rattle), or air-movement noise (subwoofer "chuffing") may be noticeable to participants at high amplitudes, or so we want to minimize amplitude to avoid this.

Our pilot had two factors: infrasound method (speaker, vibration, combined), and volume (four levels). We stayed well below occupational limits for 1-hour sound exposure (in Canada, 105 dbA), even though we only expose participants for a few minutes. We used the speaker at 90 dbA, and three settings at 2%, 4%, and 6% (of maximum system volume) below this. We selected the four vibration levels with the highest being noticeable (for the reasons mentioned above), the lowest just imperceptible, with the other two spaced evenly in between.

We recruited 6 pilot participants from other department labs. Participants sat on a chair, next to a Softbank Nao robot on a table (Fig. 3). The robot would stand up, make a sequence of happy gestures (taken from [38], with code provided by the authors), and sit down. The infrasound would begin and end with the robot motion. The robot would repeat this 12 times, once per condition (four volume levels for each of the speaker, vibration, or combined methods), counter balanced between participant using an incomplete Latin square. Participants were

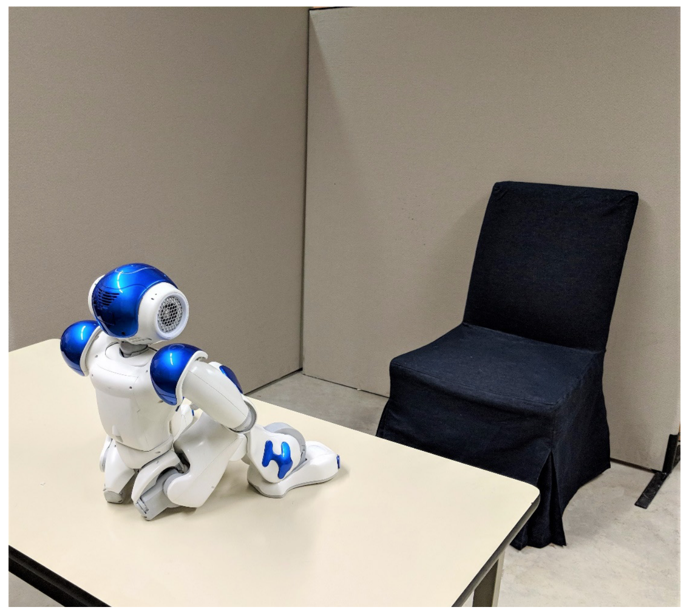

Fig. 3. During our pilot and experiments participants sit in a chair and watch a robot perform gestures, while we administer infrasound.

Fig. 2. The vibration motor (Buttkicker Low Frequency Effect Transducer) mounted to an Ikea chair. The chair skirt is lowered to conceal the equipment and wires from participants.

not told about the infrasound, but rather, were told that there were subtle variations in the robot's motions. In fact, the motions were identical, and only the infrasound changed.

After each motion, participants rated the robot's gesture in terms of affect [39]. To determine if participants noticed the infrasound we closely observed their reactions when infrasound was engaged (e.g., surprised face, looking at the chair), and after the study asked if they noticed anything odd.

Our informal analysis of results found no effect of infrasound method on rating of robot affect, where participants gave similar rating means across conditions with small variance (suggesting the ratings were not only noise). Given the lack of difference we use the combined method for our study to maximize the infrasound administered. Four participants noticed the chair vibration at its strongest, so we used one level lower for our study. No participant noticed the speaker, so we selected a volume level even higher than what we used in our pilot (still well below health standards).

D. Infrasound Safety

User and participant safety when dealing with high-output sound and vibration devices is of utmost importance. It is widely accepted that high amplitude sound energy, including infrasound, can be hazardous to one's health, leading to pain, headaches, and hearing loss; such damage is fairly common, with estimates of up to 17 percent of Americans have noise-induced hearing loss by the time they are teenagers [40]. Further, as outlined earlier ongoing regular exposure to infrasound can have mental health impacts. However, we note that exposure to infrasound is already a part of daily life (e.g., lawn mowers, large trucks, airplanes, motorcycles, etc.); the question becomes how to manage safety. In this section we outline the steps we have taken to mitigate those dangers; we hope that this can additionally be informative for other researchers.

1) Health and Safey Standards

Most countries have national or local standards and regulations relating to exposure to sound energy, which researchers and designers should be fully aware of when developing their systems. For example, researchers should consult the Canadian Centre for Occupational Health and Safety (based on the Occupational Health and Safety Act), the Occupational Safety and Health Administration office (United States Department of Labour), or the European Union Information Agency for Occupational Safety and Health.

Rather than defining a maximum sound pressure level, exposure limits are typically framed based on length of time. For example, in Canada if the length of exposure is doubled, then the acceptable loudness is halved. Further, for quick pulses of sound, standards are given for how often and how many pulses are acceptable at a given amplitude. As such, it is important to consider the character of the infrasound to be used (how often, duration, pulses, etc.) to help determine a safe level.

There are extreme cases where high energy waves (i.e., ultrasound) can be used to break down biological material [41], but this requires highly specialized equipment and focused amplitudes are not possible with typical audio equipment, and we were unable to find any evidence of serious effects (beyond hearing loss) using standard home theatre equipment, or for infrasound. Lower amplitude ultrasound itself is highly studied for medical use and considered safe internationally [42].

We will note that the acceptable maximums are safe levels at which one can work with infrasound for a given time period and not expect any health impact. That said, we were conservative in our own work, choosing levels well below acceptable maximums, and used pilot studies to determine how low we could have the sound while still achieving an effect.

2) Procedural Dilligence

Given that even common home-theater sound generation equipment is capable of extremely loud output, well above accepted health-standard levels, one must be extremely careful with sound levels when using such equipment. We took several steps (and recommend others to do likewise) to ensure safety.

First, we decided to utilize a factory-calibrated microphone (the affordable miniDSP UMIK-1) to be sure that we are measuring levels appropriately. An audio generation pipeline has many places where level of output can be modified (some in software, some in hardware), and the only reliable way to determine output level is through an external, calibrated microphone with sufficient sensitivity to be reliable.

Second, we learned very quickly that connecting and disconnecting cables can generate create a loud pulse of audio if any devices are on. Further, we found low-quality cables to give random crackles, perhaps due to low-quality connectors. Both instances could be very loud and surprising. As such, we upgraded to higher quality cables and only changed any connection if all devices were off.

Finally, given the number of variables that determine audio output level (many software mixers, hardware settings, speaker settings, etc.), we re-calibrated the audio output before every participant. Sometimes something as simple as a machine reboot could dramatically change the level generated.

V. Infrasound Experiment

We conducted an experiment to investigate if the presence of infrasound impacts how a participant perceives a robot's affective communication. Our hypothesis was simply that infrasound would impact how the robot's affective communication would be received. We hesitate to hypothesize on the direction of this impact (e.g., whether it makes the robot appear happier or sadder), given the mixed background work in psychology: some work says infrasound emphasizes mood, some says it makes mood more negative, etc.

Participants watched a robot perform actions and rated what affect they thought the robot was communicating. We had two within-participants factors: infrasound (with, without), and communicated robot emotion (happy, angry, or sad). Thus, we compare infrasound against no infrasound, and investigate interactions with the emotion being presented. We further had a between-subjects factor, infrasound duration (short or medium exposure), given the importance of this in background work.

A. Manipulations

We used three robot actions: one each designed to convey happiness, anger, and sadness. We selected these specifically because validated implementations of these motions are available for our robot [38], and the authors kindly shared their code with us. Further, these are a subset of the common six universal emotions [43] that span high and low energy and positive and negative emotions. Each motion took about 30s from start to finish, with the robot starting from a sitting position: it would stand, perform its motion, and sit down.

We administered infrasound using the speaker and vibration motor together to produce a 17hz sine-wave tone (as used in our pilots and prior work [10]). We calibrated the equipment before each participant to generate at 92 dbA (speaker, at ear level) and 1.81m/s^2 (motor, at top of chair).

Thus, within participants, we had 6 conditions: the three emotional states, with or without infrasound. We repeated each behavior twice to increase statistical power, resulting in 12 trials, counterbalanced using an incomplete Latin square (Fig. 4).

Between participants, we manipulated infrasound duration. For *short exposure*, infrasound started and stopped with robot motion, and was always off between motions. Thus, participants were only exposed while the robot was moving. For *medium exposure*, we split the study into halves of 6 trials, with one half having infrasound. Before each half was a 2-minute break, explained to participants as a calibration phase; in the infrasound case it was engaged at the beginning of the break. This ensures that participants were exposed to infrasound for at least 2 minutes before trials, and also that participants have not been exposed for at least 2 minutes prior to the no-infrasound trials.

B. Measures

At the experiment start we collected participant age, gender, and inquired about hearing impairment. At the end, after all trials, participants completed a written questionnaire to acquire feedback and check if they noticed the infrasound.

To investigate perceptions of the robot's communicated affect we employed the Russell Circumplex Model of Affect, commonly used in HRI (e.g., [1]). This model defines an affective state in two dimensions, valence and arousal: valence is how negative or positive an emotion is, and arousal represents the intensity of the emotion [44]. The model includes a third dimension, dominance, which reflects how dominant or submissive an emotion is; this dimension is less commonly used due to the difficulty in interpreting it.

After each trial (12 times in total), participants reported their interpretation of the robot's affect using the Self-Assessment Manikin (7-item variant) [45], which represents valence and arousal using pictographs. We instructed participants to select the pictographs (one per dimension) that represents the emotion that the robot was communicating. In addition, we added two 7-point questions to measure the participant's mood (one from bored to excited, one from calm to anxious).

C. Instruments and Environment

We used a Softbank Nao robot, a 22.5 inch (57.15cm) tall humanoid robot with a friendly appearance (Fig. 1,3). We used the same home theatre audio equipment as in the pilots.

The environment setup was sequestered using dividers, with the participant seated on a chair 1.2 meters away from a table with the robot on it (Fig. 1,2,3). The vibration motor, all cables, and the speaker were concealed from the participant. The speaker was placed behind one of the dividers.

D. Procedure

We explained to participants that they will help us test a robot designed to express human-like emotions by watching a robot and rating it on a set of scales. We explained that some motions will be distinctly different while others will have subtle differences. In actuality, participants only saw three different motions, repeated (sometimes with infrasound). We administered a consent form before continuing.

Following, the participant sat in the chair (Fig. 3), and we introduced the robot before starting the 12 trials. After each, the participant completed the post-trial questionnaire.

After all trials we administered the post-study questionnaire and debriefed participants on the study purpose and all deceptions, and provided an opportunity to ask questions. Overall the study took roughly one hour.

This study was approved by our institutional ethics review board, and participants were paid \$15 for their participation.

E. Results

We recruited 25 participants from our university; one outlier was removed (they recognized the experimenters and was quite talkative) resulting in 24 for analysis (M=24yrs, SD=5.0yrs, 12 female). No participant reported hearing impairment or uncorrected vision impairment. Participant rating of robot emotion on the 7-pt scale was coded from -3 to +3 for reporting.

We conducted three-way mixed-design ANOVAs with infrasound (on, off) and robot emotion (happy, angry, sad) as within-participant factors, and infrasound duration (short or medium) as between participant factors. We found a significant main effect of infrasound on reported valence of the robot motion ($F_{1,22}$=4.48, p=.04, η^2=0.17), with arousal not significant ($F_{1,22}$<1, Fig. 5.): motions with infrasound (M=.49) were perceived as having higher valence than those without (M=.26). Further, we found a main effect of robot emotion on valence ($F_{2,44}$=35.14, p<.001) and arousal ($F_{2,44}$=75.16, p<.001, specifics detailed in Fig. 6). We found no main effect of infrasound duration on the perceived robot emotion (valence $F_{1,22}$<1, arousal $F_{1,22}$=1.4, p=.25). All two-way and three-way interaction effects were not significant.

We found no effect of infrasound or motion on participant mood (all p>.05). No participant reported unusual effects or knowledge of the infrasound on the post-test questionnaire.

F. Discussion

We demonstrated that a robot can use infrasound to impact how its affective communication is received by people. Infrasound in general can make a robot's communication seem more happy (higher valence), when all other variables are held constant (Fig. 5). On the surface, this result may contradict expectations, as prior work has indicated that infrasound can have a negative

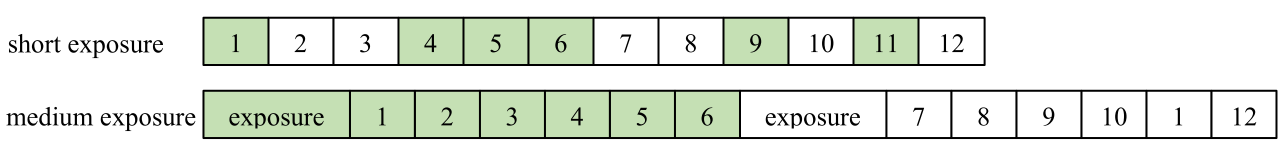

Fig. 4. Participants were assigned either short or medium infrasound exposure. For short, infrasound started and stopped with the robot motion. For medium, infrasound started at the beginning of a 2-minute break and continued for half the trials. Each box represents a trial, with shading indicating infrasound. A sample counterbalance is shown.

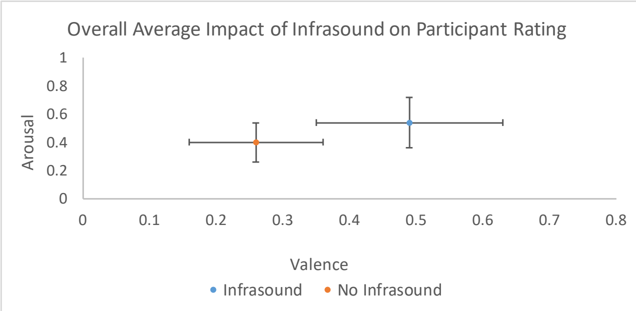

Fig. 5. The marginal means of participant ratings with infrasound (.49 valence, .54 arousal) and without infrasound (.26, .4). Valence is statistically significant (p<.05). Scale is from -3 to 3. Error bars show standard error.

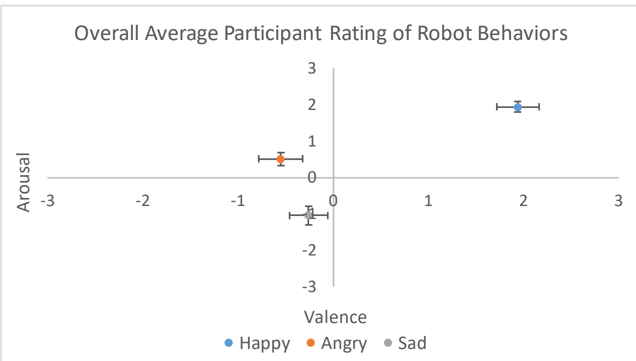

Fig. 6. The marginal means of participant ratings on each robot motion: happy (1.94 valence, 1.94 arousal), angry (-.55, .51), sad (-.26, -1.04), both dimensions statistically significant (p<.05). Error bars show standard error.

effect on mood. However, this does fall in line with some prior work that observed an amplifying effect of infrasound [9], [10]. Further, it is possible that a person may rate a robot more positively in contrast to their own mood, if infrasound indeed can make one feel down, although our own measurements on participant mood failed to find any impact. Further inquiry is needed to better understand this relationship.

The participant ratings of the robot actions (Fig. 6) serves as a manipulation check for the experiment, as the ratings match expectation: happy is positive and high energy, angry is negative and somewhat high energy, and sad is negative and somewhat low energy. This suggests that we successfully replicated the prior work [38] and our robot actions were representative of the targeted emotions. Further, this validates our use of the Self-Assessment Manikin to measure the robot communication.

We provide further results breakdown in two interaction graphs (Fig. 7., Fig. 8.). Although we note that all interactions were not statistically significant, these figures suggest that there may be undetected differences in how infrasound may impact different communicated emotions. We note that less difference is seen on the *happy* emotion, and a potential ceiling effect, where many participants rated at the top of the scale. With *angry* we see an average difference on the valence scale, and with *sad* we see difference on both valence and arousal. Future work should further investigate interactions with different emotions.

This study shows how the presence of infrasound can indeed modify how a robot's affective actions are perceived. This is particularly important to consider for large robots that produce infrasound already (e.g., from movements and large motors), or that work in locations with high levels of infrasound (such as factories). Further, this shows how a robot can use infrasound as part of its interaction toolkit, using short bursts (well within recommended health safety limits) to alter a person's interpretation of a robot's communicated affect. Given the far-reaching and difficult-to-localize nature of infrasound, this can be used in everyday environments and provides a great deal of flexibility of implementation.

While the relationship between infrasound and human psychology is still not well understood more broadly, our study contributes to the knowledge base. Our result supports the hypothesis that infrasound can modify an emotional experience, and suggests that it may make it more positive. However, ongoing work is needed to better understand the underlying mechanism behind this result.

One limitation of this study was that we generated infrasound using a combination of through-the-air and through-object sources, and so we do not know if there is any difference between the two. We conducted a follow-up experiment.

VI. INFRASOUND SOURCE EXPERIMENT

We conducted an experiment to compare infrasound from a speaker (through-the-air) with a vibration source (through-object). We varied the medium exposure protocol from the prior experiment (Fig. 4.), but instead of having infrasound either on

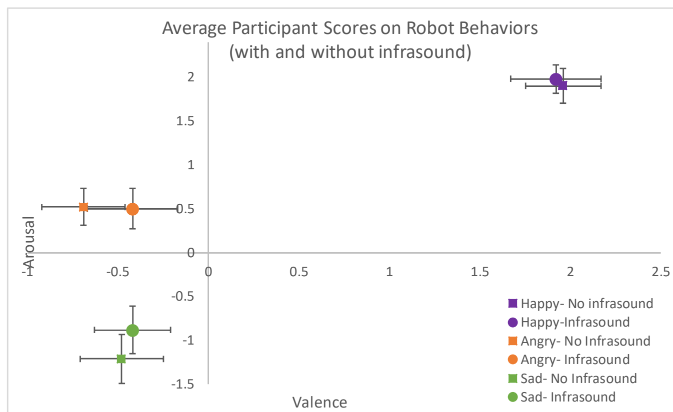

Fig. 7. Interaction between participant rating on robot motion, with and without infrasound. Interaction not significant, scale from -3 to 3. Bars show standard error.

Fig. 8. On average, how much each participant rating changed with infrasound added (individual difference factored out). Scale from -3 to 3. Bars show standard error.

or off, one half of the study had infrasound from the speaker only, and the other from the vibration motor only, with order counterbalanced between participants.

Further, given the potential ceiling effect with *happy* and small differences (Fig. 7.,8), we only included the *angry* and *sad* actions. This resulted in 4 cases: infrasound method (speaker, vibration), by robot motion (angry, sad), with each combination shown twice to increase statistical power, resulting in 8 trials. This study was approved by our institutional ethics review board, and participants were paid $15 for their participation.

A. *Results*

We recruited 13 participants, but removed one as an outlier: they immediately noticed the infrasound (vibration motor), resulting in 12 for analysis (M=23yrs, SD=4.8yrs, 6 female).

We conducted two-way repeated-measures ANOVAs with infrasound source (speaker, vibration motor) and robot emotion (angry, sad) as within-participant factors. We found no effect of infrasound source on rated valence ($F_{1,11}$=1.06, p=.32) or arousal ($F_{1,11}$<1, Fig. 9). We found a main effect of robot motion on arousal ($F_{1,11}$=6.20, p=.03), with *anger* having higher arousal (M=.80) than *sad* (M=-.4, Fig. 10), while valence was not significant ($F_{1,11}$<1).

B. *Discussion*

We found no difference between the two infrasound methods on participant rating of the valence or arousal dimensions. As shown in Fig. 9, the distributions heavily overlap. Looking deeper, Fig. 10 shows the interaction with the emotion shown, which illustrates the lack of impact: for both emotions the distributions highly overlap.

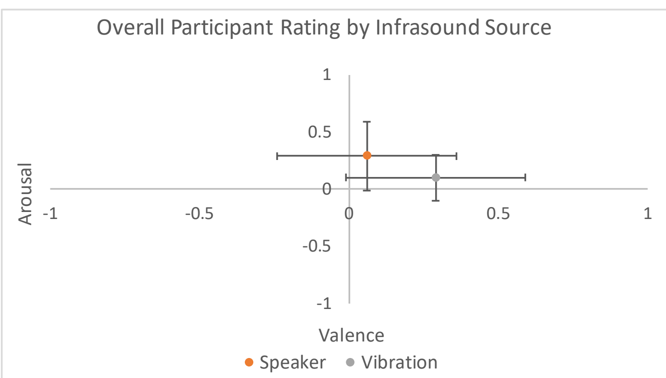

Fig. 9. Average participant rating on robot motion by infrasound source. Differences not significant. Scale from -3 to 3. Bars show standard error.

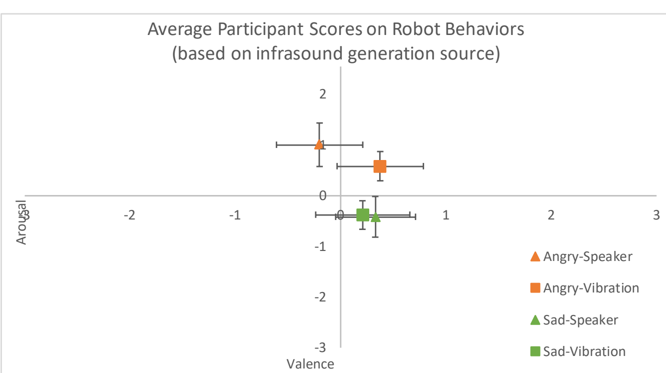

Fig. 10. Interaction between participant rating on motion and infrasound generation source. Interaction not significant, bars show standard error.

One caveat with our study is that we did not include a no-infrasound condition, which precludes us from specifically investigating the effect of each infrasound source separately. However, our result suggests there is no strong difference between the generation methods, and lends support to the idea that either method may be feasible for use by a robot. However, a future study should be conducted to better understand the relationship between the generation methods.

VII. Limitations and Future Work

The broader study of infrasound and human psychology is ongoing, and the inquiry of how robots can use infrasound will need to be continually updated as the field improves.

Our work demonstrated that a robot can use infrasound in a controlled laboratory environment. Ongoing work needs to investigate a robot using infrasound in more organic environments, such as in a crowded space or in a workplace.

For this initial inquiry we specifically targeted a robot communicating specific pre-programmed gestures out of context. Social interaction with a robot is more complex, and infrasound should be explored more broadly. For example, how can a robot use infrasound in a dynamic situation such as conflict, or during work, to shape interaction? Can a robot use infrasound to impact perceptions and interaction among groups and between individuals? Ongoing work needs to explore infrasound in a wider range of contexts.

We only used specific sine-wave infrasound tones and frequencies. While based on prior work, it is possible that more dynamic infrasound (e.g., changing amplitudes, changing tone, more complex textures) may change impact.

VIII. Conclusion

We conducted an exploration of how the presence of infrasound may impact how a social robot's affective communications are perceived by people. Further, we demonstrated two methods that a robot itself could use to generate infrasound. Specifically, our experiment results showed that a robot can use infrasound to change how its affective communication is perceived: adding infrasound makes the communication seem more positive. Further, we conducted a follow-up experiment that failed to find a difference between infrasound conveyed through the air (using a speaker) or through an object (using a vibration motor), suggesting a versatility of implementation.

We believe that it is important to recognize that the presence of infrasound will impact how people interact with robots, and those creating robots in factories, for airplanes, on large trucks, or in other places with infrasound, should consider this. Further, we believe that infrasound is a unique tool that robots can use when working with people. The long-distance properties, and versatility of source location (as humans cannot localize it) provide a wealth of interaction and implementation possibilities. Further, in our experiments only one person noticed the infrasound, suggesting that most people may not be aware of it. While many questions remain, such as how infrasound may impact more complex interactions, our initial work serves as a proof of concept that we hope will inspire a body of work on infrasound for human-robot interaction.

REFERENCES

[1] M. Sharma, D. Hildebrandt, G. Newman, J. E. Young, and R. Eskicioglu, “Communicating affect via flight path exploring use of the laban effort system for designing affective locomotion paths,” ACM/IEEE Int. Conf. Human-Robot Interact., pp. 293–300, 2013.

[2] S. H. Seo, D. Geiskkovitch, M. Nakane, C. King, and J. E. Young, “Poor Thing! Would You Feel Sorry for a Simulated Robot?,” Proc. Tenth Annu. ACM/IEEE Int. Conf. Human-Robot Interact. - HRI ’15, pp. 125–132, 2015.

[3] D. Y. Geiskkovitch, D. Cormier, S. H. Seo, and J. E. Young, “Please Continue, We Need More Data: An Exploration of Obedience to Robots,” J. Human-Robot Interact., vol. 5, no. 1, pp. 82–99, 2016.

[4] T. Shibata and K. Wada, “Robot therapy: A new approach for mental healthcare of the elderly - A mini-review,” Gerontology, vol. 57, no. 4, pp. 378–386, 2011.

[5] J.-S. Eom, S.-H. Kim, S.-S. Jung, and J.-H. Sohn, “Low Frequency Noise and It’s Psychological Effects.,” J. Ergon. Soc. Korea, vol. 33, no. 1, pp. 39–48, 2014.

[6] J. H. Mühlhans, “Low frequency and infrasound: A critical review of the myths, misbeliefs and their relevance to music perception research,” Music. Sci., vol. 21, no. 3, pp. 267–286, 2017.

[7] B. L. Wei, “Physiological Effects of Audible Sound: AAAS Symposium, 28-30 December 1969, Boston,” Science (80-.)., vol. 166, no. 3904, pp. 533–535, 1969.

[8] V. Tandy and T. R. Lawrence, “The ghost in the machine,” Journal-Society Psych. Res., vol. 62, pp. 360–364, 1998.

[9] “Sounds like terror in the air,” The Sydney Morning Herald, 2003.

[10] S. Angliss, “Soundless Music,” Most, 2002. .

[11] H. Admoni and B. Scassellati, “Social Eye Gaze in Human-Robot Interaction: A Review,” J. Human-Robot Interact., vol. 6, no. 1, p. 25, 2017.

[12] K. Nakagawa, M. Shiomi, K. Shinozawa, R. Matsumura, H. Ishiguro, and N. Hagita, “Effect of Robot’s Whispering Behavior on People’s Motivation,” Int. J. Soc. Robot., vol. 5, no. 1, pp. 5–16, 2013.

[13] M. Shimada, Y. Yoshikawa, M. Asada, N. Saiwaki, and H. Ishiguro, “Effects of observing eye contact between a robot and another person,” Int. J. Soc. Robot., vol. 3, pp. 143–154, 2011.

[14] D. Sakamoto and T. Ono, “Sociality of Robots: Do Robots Construct or Collapse Human Relations?,” in Proc. ACM/IEEE international conference on Human-Robot Interaction - HRI ’06, 2006, pp. 355–356.

[15] C. Bartneck, T. Bleeker, J. Bun, P. Fens, and L. Riet, “The influence of robot anthropomorphism on the feelings of embarrassment when interacting with robots,” Paladyn J. Behav. Robot., vol. 1, no. 2, pp. 109–115, Aug. 2010.

[16] C. Bartneck, M. van der Hoek, O. Mubin, and A. Al Mahmud, “‘Daisy, Daisy, give me your answer do!,’” in Proceeding of the ACM/IEEE international conference on Human-robot interaction - HRI ’07, 2007, p. 217.

[17] M. F. Jung, N. Martelaro, and P. J. Hinds, “Using Robots to Moderate Team Conflict,” in Proc. ACM/IEEE international conference on Human-Robot Interaction - HRI ’15, 2015, pp. 229–236.

[18] D. Rocchesso and S. Serafin, “Sonic Interaction Design,” Int. J. Hum. Comput. Stud., vol. 67, no. 11, pp. 905–906, 2009.

[19] R. Diaz-marino and S. Greenberg, “CAMBIENCE : A Video-Driven Sonic Ecology for Media Spaces,” pp. 3–4, 2006.

[20] L. Langeveld, R. van, R. Jansen, and E. Ozc, “Product Sound Design: Intentional and Consequential Sounds,” Adv. Ind. Des. Eng., 2013.

[21] J. Mullenbach, C. Shultz, J. E. Colgate, and A. M. Piper, “Exploring Affective Communication Through Variable - Friction Surface Haptics,” in CHI 2014, 2014, pp. 3963–3972.

[22] S. Song and S. Yamada, “Expressing Emotions through Color, Sound, and Vibration with an Appearance-Constrained Social Robot,” Proc. 2017 ACM/IEEE Int. Conf. Human-Robot Interact. - HRI ’17, pp. 2–11, 2017.

[23] H. Tennent, D. Moore, M. Jung, and W. Ju, “Good Vibrations: How Consequential Sounds Affect Perception of Robotic Arms,” pp. 1–8, 2017.

[24] D. Moore, H. Tennent, N. Martelaro, and W. Ju, “Making Noise Intentional: A Study of Servo Sound Perception,” 2017.

[25] H. Kozima, M. P. Michalowski, and C. Nakagawa, “Keepon: A playful robot for research, therapy, and entertainment,” Int. J. Soc. Robot., vol. 1, no. 1, pp. 3–18, 2009.

[26] A. Davis et al., “Aging and Hearing Health: The Life-course Approach,” Gerontologist, vol. 56, no. Suppl_2, pp. S256–S267, 2016.

[27] M. a. Bellmann, “Perception of Whole-Body Vibrations: From basic experiments to effects of seat and steering-wheel vibrations on the passenger’s comfort inside vehicles,” Akustik.Uni-Oldenburg.De, no. November, p. 209, 2002.

[28] B. Berglund, P. Hassmén, and R. F. S. Job, “Sources and effects of low-frequency noise,” J. Acoust. Soc. Am., vol. 99, no. 5, pp. 2985–3002, 1996.

[29] J. C. Middlebrooks and D. M. Green, “Sound Localization By Human Listeners,” no. 234046, pp. 26–61, 1991.

[30] W. M. Hartmann, “How we localize sound,” Phys. Today, vol. 52, no. 11, pp. 24–29, 1999.

[31] M. Schust, “Effects of low frequency noise up to 100 Hz,” Noise Heal., vol. 6, no. 23, pp. 73–85, Apr. 2004.

[32] Å. DANIELSSON and U. LANDSTRÖM, “Blood Pressure Changes in Man during Infrasonic Exposure: An Experimental Study,” Acta Med. Scand., vol. 217, no. 5, pp. 531–535, 1985.

[33] M. J. Evans and W. Tempest, “Some effects of infrasonic noise in transportation,” J. Sound Vib., vol. 22, no. 1, pp. 19–24, 1972.

[34] C. S Harris and D. L Johnson, “Effects of Infrasound on Cognitive Performance,” Aviat. Space. Environ. Med., vol. 49, pp. 582–586, 1978.

[35] G. Leventhall, “A Review of Published Research on Low Frequency Noise and its Effects. Report for DEFRA EPG 1/2/50,” no. May, pp. 1–88, 2003.

[36] G. Leventhall, “What is infrasound?,” Prog. Biophys. Mol. Biol., vol. 93, no. 1–3, pp. 130–137, 2007.

[37] C. C. for O. H. and Safety, “Noise - Occupational Exposure Limits in Canada,” 2018. .

[38] M. S. Erden, “Emotional Postures for the Humanoid-Robot Nao,” Int. J. Soc. Robot., vol. 5, no. 4, pp. 441–456, 2013.

[39] A. Mehrabian and J. A. Russell, “The basic emotional impact of environments,” Percept. Mot. Skills, vol. 38, no. 1, pp. 283–301, 1974.

[40] C. H. Elisabeth Henderson, Marcia A. Testa, “Prevalence of Noise-Induced Hearing-Threshold Shifts and Hearing Loss Among US Youths,” Pediatrics, vol. 127, no. 1, 2011.

[41] J. (Hans) van Leeuwen, B. Akin, S. K. Kumar, S. Sung, and D. Grewell, “Ultrasound pre-treatment of waste activated sludge,” Water Supply, vol. 6, no. 6, 2006.

[42] B. L et al., “Ultrasound screening in pregnancy: a systematic review of the clinical effectiveness, cost-effectiveness and women’s views.,” Heal. Technol Assess, vol. 4, no. 6, 2000.

[43] P. Ekman, “An argument for basic emotions,” Cogn. Emot., vol. 6, no. 3–4, pp. 169–200, May 1992.

[44] J. Posner, J. A. Russell, B. S. Peterson, J. A. Russellc, and B. S. Peterson, “The circumplex model of affect: An integrative approach to affective neuroscience, cognitive development, and psychopathology,” Dev. Psychopathol., vol. 17, no. 3, pp. 715–734, 2005.

[45] J. Morris, “Observations: SAM: the Self-Assessment Manikin; an efficient cross-cultural measurement of emotional response,” J. Advert. Res., no. December, 1995.