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Why can you hear a difference between pouring hot and cold water? An investigation of temperature dependence in psychoacoustics.

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ABSTRACT

Studies have shown that listeners can distinguish between hot and cold water being poured based solely on sonic properties, yet the cause of this is unknown. This acoustic perception of temperature is an interesting aspect of multisensory perception and integration. In this paper, a series of experiments were performed to investigate the characteristics of auditory information when water is poured at different temperatures into various containers. Based on the results, it attempts to find physical and psychoacoustic explanations for the phenomenon.

1 Nomenclature

H = height of cylindrical container (m)
D = diameter of cylindrical container (m)
a = thickness of cylindrical container's wall (m)
L = length of the air column (m)
R = radius of cylindrical container (m)
c = speed of sound in the air (m/s)
Y = Young's modulus (N/m^2)
ρ_g = density of the container (kg/m^3)
ρ_l = density of the liquid (kg/m^3)
h = liquid level (m)
h_m = maximum liquid level in the pouring (m)
v = pouring speed (m/s)
t = pouring time (s)
T = temperature of water $(^\circ C)$
f_{air} = resonance frequency of the air column (Hz)
f_0 = vibration frequency of the container (Hz)
ω_0 = angular vibration frequency of the container (rad/s)
f_{obj} = vibration frequency of the container and the liquid as a whole (Hz)
ω_{obj} = angular vibration frequency of the container and the liquid as whole (rad/s)
ξ = parameter related to physical properties of the container and the liquid

2 Introduction

The acoustic information of pouring sounds has attracted the attention of scientists since the beginning of this century. In 2000, [1] reported an experiment to explore people's ability to control vessel filling simply based on acoustic information. In 2005, Kees van den Doel introduced physical models for synthesizing liquid sounds[2]. In 2010, Andy Farnell introduced a model for synthesizing the sound of pouring water in his book[3]. These researches focused mainly on the sound of pouring, but not so much on the temperature of the liquid.

Recently, scientists have started to focus on the information about the properties of the liquid or the container which the sound of pouring could convey. In 2015, [4] reviewed researches that has investigated people's ability of perceiving the temperature of a beverage, the level and/or type of carbonation, the viscosity of the liquid, and even the shape of the bottle or container based on sound alone. The results shows that in terms of discriminating the meaning of pouring sounds, participants performed significantly better than chance. Further work by the authors showed that cold water was associated with high pitch and faster tempo [5].

Researchers from University of Oxford, in collaboration with advertising agency Condiment Junkie who use sound design in branding and marketing, published a 2013 paper on people's ability to hear a difference between pouring hot and cold water [6]. The experiment was first described in Condiment Junkie's blog, and received lots of attention in the popular press and social media. For example, one YouTube video about this phenomenon has received over 1,000,000 views.

From the sound samples posted by Condiment Junkie on SoundCloud, there are clear differences between the sounds of pouring hot and cold water into containers. To see how people react to the differences, they conducted experiments in which they invited participants to tell whether the water being poured is hot or cold based solely on listening to the recordings, and posted the results on a National Public Radio (NPR) piece. Though not a controlled experiment, more than ninety percent of the respondents could distinguish hot and cold water accurately just by hearing the sound.

However, there was not a good explanation as to why we hear the difference. [6] mentioned modifying the temperature of the sound by changing the equalization (EQ), but did not give a justification or explanation for this. The YouTube video simply states that 'the change in the splashing of the water changes the sound that it makes because of various complex fluid dynamic reasons'. According to Scott King, one of the founders of Condiment Junkie, 'there tends to be more bubbling in a liquid that's hot... you tend to get higher frequency sounds from it,' but further discussion on NPR noted 'Cold water is more viscous... That's what makes that high pitched ringing.' On Physics Stack Exchange, the most dominant factor people suggest is that the viscosity changed with the temperature. Other factors suchas surface tension and density are also mentioned. However, all of this is only speculation.

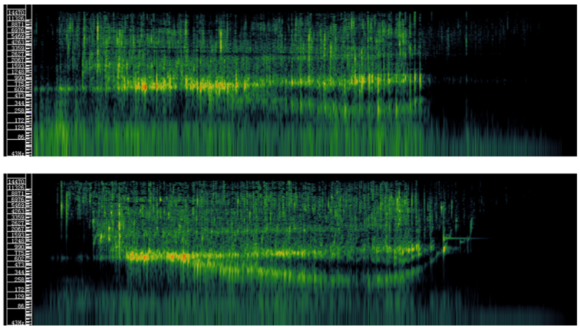

Fig. 1: Spectrograms of audio samples of pouring hot (top) and cold (bottom) water

This paper aims to provide a deeper understanding as to why listeners can distinguish between hot and cold water being poured based solely on sonic properties. A series of experiments were performed to investigate the characteristics of auditory information when water is poured at different temperatures into various containers. Based on the results, it attempts to find physical and psychoacoustic explanations for the phenomenon. This research could be used for sound synthesis of pouring, and interactive design in which people can control the temperature of the water and the pouring sound will change accordingly. It could also be of great interests to scientists focusing on psychoacoustics.

2.1 Initial analysis

To discover possible differences of the sound of pouring hot and cold water, and inform the design of our experiments, we first performed rudimentary analysis of the audio samples posted by Condiment Junkie on Soundcloud. Fig. 1 are the spectrograms of samples of pouring hot and cold water into a glass. Frequency is on a log scale.

The same frequencies are present in both signals. There is a strong, dominant frequency that seems to be logarithmically increasing from about 650 Hz to just over 1 kilohertz, and there is a second frequency that appears a little later, starting at around 720 Hz, falling all the way to 250 Hz, then climbing back up again. These values are approximately the same in both hot and cold cases. The most visible difference is that cold water has a much stronger second frequency (the one that dips). There also seems to be more stronger 'noisy' low frequency components in hot water signal, though this may be just an artifact of the low quality, noisy recording.

3 Background knowledge

Based on previous research on the sound of pouring water, the sources of sound during pouring can be divided into resonance of the air column in the container, vibration of the container and the water as a whole, and water sounds (especially bubble sounds).

3.1 Resonance of the air column

[1] gives a Eq., originally from [7], for the fundamental resonance frequency of the air column $f_{air}(L)$ in a tube closed at one end and open at the other;

$$f_{air}(L) = \frac{c}{4L + 0.62R} \tag{1}$$

The constant 0.62 is empirically determined. The shorter the length L of the air column is, the higher the resonance frequency is.

3.2 Vibration of the container and the water as a whole

The vibration of a thin-walled cylinder f_0 of radius R and height H can be calculated by Eq. [8],

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{3Y}{5\rho_g}\frac{a}{R^2}}\sqrt{1+\frac{4}{3}(\frac{R}{H})^4} \tag{2}$$

where Y is the Y is Young's modulus (N/m^2), ρ_g is the density of the container (kg/m^3), and a is the thickness of cylindrical container's wall (m).

According to 2, the vibration frequency of the container is decided by the physical property of the container itself.

[9] describes how liquid of height h in the glass influences the vibration frequency of the container and the liquid as a whole. It gives an equation for the relation between the fundamental angular frequency of the whole object and that of an empty container:

$$\frac{\omega_0^2}{\omega_{obj}^2} = 1 + \xi(\frac{h}{H})^3 \tag{3}$$

where ω_0 is the angular vibration frequency of the container (rad/s), ω_{obj} is the angular vibration frequency of the container and the liquid as whole (rad/s), and ξ is a parameter related to physical properties of the container and the liquid.

$$\xi = \frac{4\rho_l R}{9\rho_g a} \tag{4}$$

ρ_g is the density of the container (kg/m^3) and ρ_l is the density of the liquid (kg/m^3). Inverting 3 and using $\omega = 2\pi f$ to replace angular frequency ω with frequency f, we have:

$$f_{obj}(h) = \frac{f_0}{\sqrt{1+\xi(\frac{h}{H})^3}} \tag{5}$$

According to 5, the higher the water level, the lower the vibration frequency.

3.3 Bubble sounds

[2] noted that 'water by itself hardly makes any sounds at all.' It is only when the air is trapped in the water, helping to form bubbles, that the sound can be heard. Bubble sounds are the main part of liquid sounds. [2] describes the theory of how bubbles are formed when droplets or solids impact water, which also describes water being poured.

4 Hypotheses

Suppose that at time $t = 0$, the container is empty, The vessel is then filled at a constant speed v at certain temperature. For the resonance of the air column in the container (Eq. 1), the air column length L at time t could be written as $(H - vt)$. So 1 could be written as:

$$f_{air}(t) = \frac{c}{4(H - vt) + 0.62R} \tag{6}$$

From Eq. 6, there are two factors that could influence the resonance frequency of the air column inside: the size of the container and the pouring rate. Here we ignore the change of the speed of sound in the air. If the height or the radius of the container increases, then the initial frequency of the air column decreases. If the size of the container is fixed, when the pouring rate increases (that is, v increases), f_{air} will increase faster, which also means the slope of the frequency line gets steeper.

For the vibration of the container and the liquid as a whole (Eq. 5), the water level h equals vt. 5 could be writen as:

$$f_{obj}(t) = \frac{f_0}{\sqrt{1+\xi(\frac{vt}{H})^3}} \tag{7}$$

So as a vessel filled with water has a progressively higher water level, the fundamental resonance frequency of the air column f_{air} increases, whereas the fundamental vibrant frequency of the whole object f_{obj} decreases.

There are two main frequency lines in the spectrograms shown in 1. The rising frequency line could be related to the resonance of the air column in the container. As the fluid is poured, the length of the air column decreases and the resonant frequency of the remaining ‘chamber’ increases. The other frequency line falls at first, so it may be caused by the vibration of the container and the liquid as a whole. As more and more liquid is poured into the container, the weight of the container and the water as a whole increases, leading to a lower vibration frequency.

However, though these equations may account for the most prominent aspects of the two spectrograms, they offer no direct explanation for the temperature dependence. Deeper analysis required focused experiments.

5 Experimental design

The experiments were conducted in the listening room of the Center for Digital Music (C4DM) at Queen Mary University of London. The listening room is an isolation booth which provides very few echoes. A water dispenser with a fixed pouring height and a temperature adjustment was used to keep the pouring speed at a constant rate. After a thorough comparison of different kinds of microphones and recording interfaces, we selected an AKG C451B microphone and Fireface 800 audio interface. The AKG C451B is a cardioid condenser microphone, with frequency response as shown in 2.

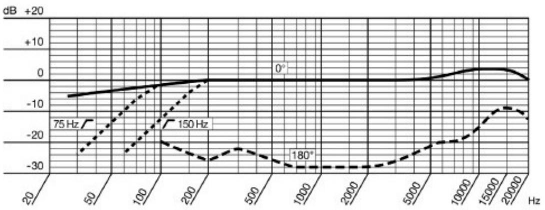

Fig. 2: Parameters of AKG C451B

As hot and cold water are feelings or sensations defined by people, there are no fixed values for them. We regarded hot water as water with a temperature higher than 85 Celsius degree, and cold water as water with a temperature lower than 15 Celsius degree. The temperature of the water being poured was calculated immediately after finishing the recording of each sound of pouring water.

Before conducting the formal experiments, some initial testing was performed to find suitable settings for the amplifier and the distance between the microphone and the water dispenser. The amplitude of both hot and cold water recordings should be within the maximum possible dynamic range to minimize audio distortion.

We poured hot and cold water into three cylindrical glass containers with different sizes. Spectrograms were acquired in both Matlab and Sonic Visualiser using the short-time Fourier transform, with sampling frequency 44.1 kHz, window size 2048 and overlap 50%. Analysis confirmed that the same frequencies exist in spectrograms of both hot and cold water signals for every container, and that they roughly matched the theoretical predictions from Eq.s 6 and 7. We then poured hot and cold water directly onto the ground, to remove the effect of the container. This helped provide information about which part of the frequencies in the spectrograms represents just water sounds, especially bubble sounds.

Next, we varied the temperature of the water, when pouring water into the same container at the same pouring height, to see how the frequency and intensity change as a function of water temperature.

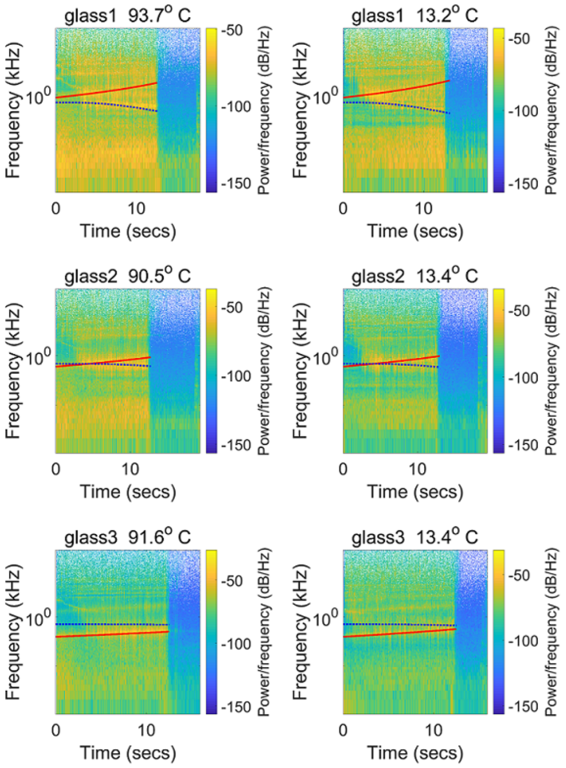

Fig. 3: Pouring hot (left) and cold (right) water into glass1, glass2 and glass3 (top to bottom)

Table 1: Spectrograms of pouring water into three cylindrical glasses with different sizes with predicted resonance and vibration frequencies in red and blue, respectively.

Number	glass1	glass2	glass3
H / mm	68	114	188
D / mm	92.04	90.68	91.21
a / mm	2.09	2.21	2.33
T	93.7°	90.5°	91.6°
h_m / mm	48	50	46
t / s	12.59	12.768	12.5
ρ_l (kg/m^3)	962.80	964.99	964.24
T	13.2°	13.4°	13.4°
h_m / mm	53	55	65
t / s	13.272	13	12.5
ρ_l (kg/m^3)	999.35	999.33	999.33

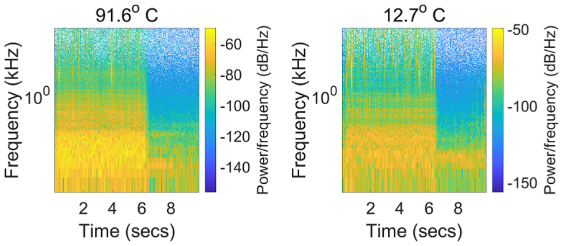

Fig. 4: Pouring hot (left) and cold (right) water onto the flat surface

6 Results and analysis

The details of pouring hot and cold water into three cylindrical glass containers are shown in Table 1.

Fig. 3 shows the corresponding spectrograms with predicted frequency components. The red solid line represents Eq. 6, which is the theoretical resonance frequency of the air column in the container. The blue dotted line represents Eq. 7, which is the theoretical vibration frequency of the container and the water as a whole.

According to the spectrogram, the value of the dominant frequencies of hot and cold water signals for the same container are very similar. The theoretical equations agree with the actual frequencies very well, which shows that resonance of the air column and vibration of the container and the liquid as a whole are two main sources of the sound during the pouring.

The spectrograms of pouring hot and cold water directly onto the flat surface are shown in Fig. 4. Here, a wooden floor was used as the flat surface. The temperature of hot water is 91.6°, and the temperature of the cold water is 12.7°. The duration of pouring is 6.508 seconds for each. The increasing and the decreasing frequency lines have disappeared. The value of the frequency and the intensity in each short time period does not change with time. Since there's no sound source coming from the container, the sound should come mostly from water sounds, and impacts on the wooden floor.

The results of pouring water at different temperatures into the same glass from the same pouring height are shown in Table 2. The frequency lines and their intensities as a function of temperature are shown in Fig. 5, Fig. 6, respectively.

Table 2: Pouring water at different temperatures from the same height into the same glass container.

T	h_m / mm	t / s	ρ_l (kg/m^3)
8.2°	90.0	31.000	999.84
20.0°	96.5	31.015	998.21
34.1°	95.0	30.800	994.34
45.6°	96.0	30.612	989.96
53.0°	97.0	30.765	986.65
62.0°	97.0	30.459	982.16
70.5°	97.0	30.441	977.49
81.2°	95.0	30.594	971.05
95.3°	93.5	30.753	961.69

Note. The size of the container: Height $H = 114mm$, diameter $D = 90.68mm$, thickness $a = 2.21mm$. The pouring height is 34cm.

From Fig. 5, the values of the frequencies are close to each other and the trends of the frequency lines are similar at different temperatures. However, according to Fig. 6, as temperature is increased, two main effects can be observed. First, the intensities of both the resonance of the air column and the vibration of the container with water inside decrease significantly. Second, the intensities of the vibration of the container with water inside goes down more quickly than that of the resonance of the air column.It can be seen that when the temperature of water is under 20°C, the intensities of the vibration of the container and the water as a whole is stronger than that of the resonance of the air column, while it is quite the opposite when the temperature is close to 100°C. It suggests that when pouring cold water into the container, the overall intensity of the vibration of the whole object is stronger than that of the resonance of the air column, but during the pouring of hot water, the overall intensity of the vibration of the whole object is weaker than that of the resonance of the air column.

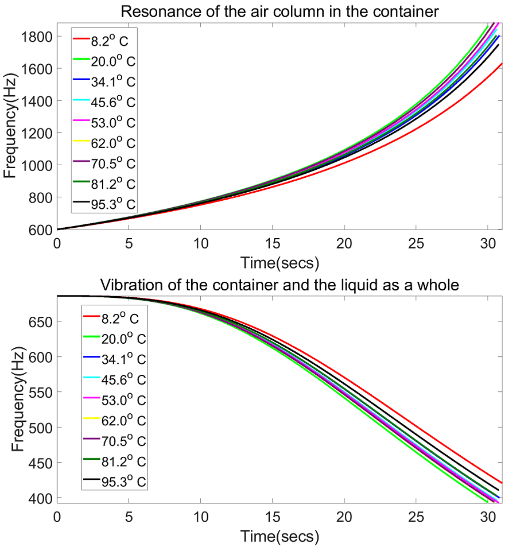

Fig. 5: Values of resonance and vibration frequencies at different temperatures

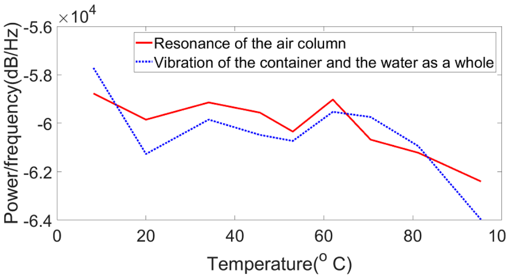

Fig. 6: Intensities for resonance and vibration frequency lines at different temperatures

7 Summary

Our research suggests that during the pouring there are mainly three sources of sound; resonance of the air column in the container, vibration of the container and the water as a whole, and water sounds. What's more, the sound of the vibration of the container and the liquid as a whole takes a dominant role in the sound of pouring cold water, while the sound of the resonance of the air column in the container takes a dominant role in the sound of pouring hot water. The difference of the overall intensities of different sound sources may be one of the reasons that people can hear the difference of hot and cold water just by the sound.

This research represents a step forward. It shows how temperature affects the observed signals, and what accounts for the aspects that are affected. But none of the theory gives an explanation for the temperature dependence in these aspects. In particular, though frequency terms are predicted, their amplitudes are not, yet these amplitudes exhibit the strongest dependence on temperature. Thus, this work highlights the limitations in theory as well as suggesting directions towards more significant advances.

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